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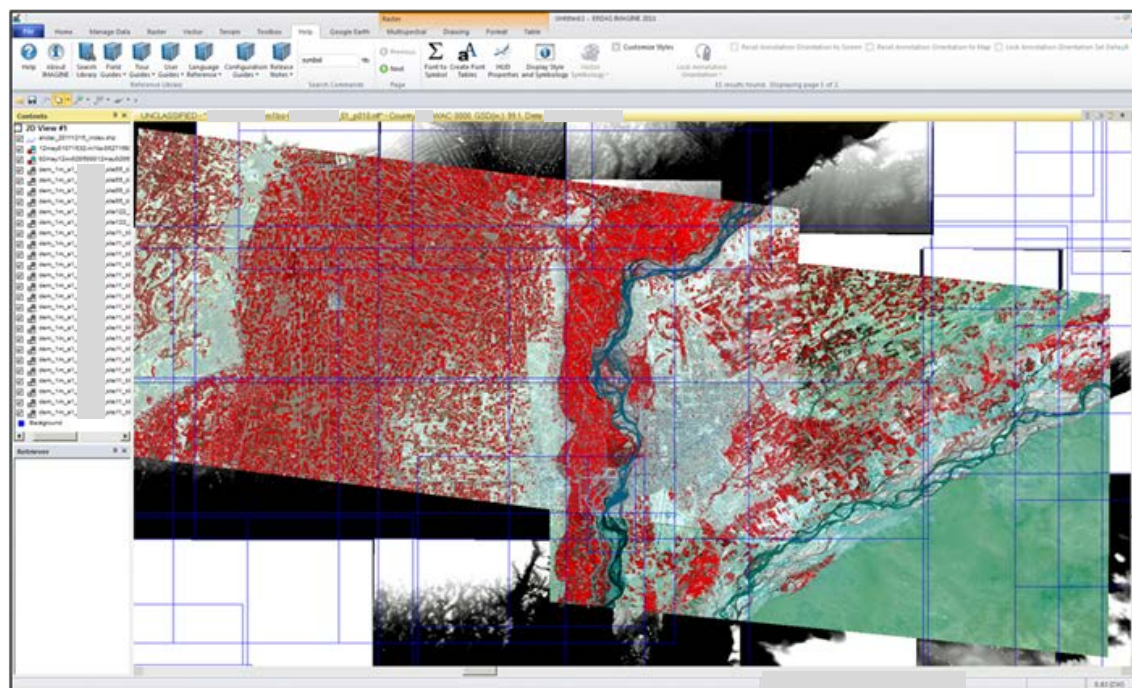
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Creating Orthographically Rectified Satellite Multi-Spectral Imagery with High Resolution Digital Elevation Model from LiDAR

A Tutorial

Roger O. Brown

August 2014



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Creating Orthographically Rectified Satellite Multi-Spectral Imagery with High Resolution Digital Elevation Model from LiDAR

A Tutorial

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Abstract

Orthoimages are used to produce image-map products for navigation and planning, and serve as source data for advanced research, development, testing, and evaluation of feature extraction methods. This tutorial describes procedures for making orthoimages from Light Detection and Ranging (LiDAR) Digital Elevation Models (DEM) and from commercial satellite Multi-Spectral Imagery (MSI) in the National Imagery Transmission Format (NITF) with Rational Polynomial Coefficients (RPC). Orthoimages rectify digital imagery to remove geometric distortions caused by the varying elevations of the exposed terrain features, and by exterior and interior orientations of the sensor. When orthoimages are combined, the resulting mosaic covers a wider area and contains less visible seams, which makes the map easier to understand. RPC replace the actual sensor model while processing the original MSI. This generic replacement sensor model is provided with the distributed imagery to simplify the process of removing the geometric distortions so image processing software can create orthoimages without using the actual sensor model, which is often not provided. The DEM and MSI also become better registered together after producing the orthoimage by using the RPC. This assists feature extraction and segmentation when the DEM is added as extra data bands to the MSI.

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Preface

This study was conducted for the U.S. Army Geospatial Research Laboratory under the “Data Level Enterprise Tools” project. The technical monitors were Michael Campbell (TR-S), Brian Graff (TR-G), and James Eichholtz (TR-S).

The work was performed by the Data Signature Analysis Branch (CEERD-TR-S) of the Topographic Research Division (CEERD-TR), U.S. Army Engineer Research and Development Center, Geospatial Research Laboratory (ERDC-GRL). At the time of publication, Jennifer Smith was the Branch Chief, CEERD-TR-S; Dr. Eric Zimmerman was the Division Chief, CEERD-TR; and Ritch Rodebaugh, CEERD-TV-T, was the Technical Director for overseeing the CEERD-TR Division. The process described in this document was tested by Alana Hubbard and Chris D’Errico from the U.S. Army Geospatial Center (AGC) Imagery Office, and by the AGC Military Support Team of SFC Roger Adkins and SGT Clay Weaver. The Topographic Research Division works closely with Dr. Joseph Fontanella, Director of the U.S. Army Geospatial Center and the Geospatial Research Laboratory (CEERD-GRL).

The Commander and Executive Director of ERDC is COL Jeffrey R. Eckstein, and the Director for Research and Development plus Chief Scientist of ERDC is Dr. Jeffery P. Holland.

1 Introduction

This *Introduction* section covers the following topics:

1. The reasons for orthorectification – why it is done.
2. Digital Elevation Models (DEM) that are derived from Light Detection and Ranging (LiDAR).
3. Comparing LiDAR DEM and WorldView-2 Multi-Spectral Imagery (MSI) Ground Sample Distance (GSD) resolutions.
4. The methods of orthorectification – how it is done.
5. Sensor models that use Rational Polynomial Coefficients (RPC).

Chapter 2, “Procedures,” describes the step-by-step process for using the DEM, MSI and RPC to construct an orthoimage. The appendixes include supplemental detail.

1.1 Reasons for orthorectification

The Army Geospatial Center and the Engineer Research and Development Center, Geospatial Research Laboratory (ERDC-GRL) supplies orthoimage mosaics that are products to aid tactical decisions and improve situational awareness during military operations (HQDA, 2001; HQUSACE, 2002). The orthorectification process is a practical way to register the DEM and raw MSI together for synergistic analysis of both datasets.

Raw satellite or aerial imagery has distortions regarding the positional accuracy of its coordinates because the nearly vertical overhead imagery contains horizontal displacement based on the physical terrain. Angular distortions can occur from the perspective views of the sensor as it looks at the terrain, and distortions may occur in completely flat areas (Agouris, et al., 2004; Miller, 2013; Scarpace, 2013). The position and angular attitudes of the sensor are commonly called its “exterior orientation.” The position of the sensor also changes along its flight path while scanning the terrain so that other distortions occur while the sensor scans the terrain, including distortions caused by: (1) the relationship between the focal center and the image plane of the sensor, and (2) the electrical or mechanical scanning motion of the sensor array that measures the energy reflected or emitted from the terrain.

Measurements of location in this raw imagery are inaccurate unless these displacements and distortions are first removed. Removing these distortions also facilitates the projection of the initially constructed planimetric orthoimage from its geocentric latitude and longitude coordinates into other map projections, say Universal Transverse Mercator (UTM) for example. These distortions are best described by the mathematics and projective geometry of photogrammetry (Forstner & Wrobel, 2013; Mugnier, et al., 2013).

This raw overhead imagery may be corrected by removing the combined displacements and distortions through a process called “orthorectification,” which results an orthographically rectified image commonly called an “orthoimage.” Making orthoimages is a complex process that requires: (1) a DEM of the terrain heights, (2) imagery from an airborne or satellite sensor, and (3) a sensor model for projective equations from the exposed terrain to the sensor image.

The accuracy of the orthoimage is limited by the vertical accuracy of the DEM, and by the accuracy of the sensor model describing its exterior and interior orientations, when exposing the image of the terrain. A cursory check (or a more detailed analysis) of its accuracy should be done to assess the quality of the orthoimage. Note that this tutorial gives more attention to the rendering aspects of orthoimages.

1.2 DEM derived from LiDAR

A DEM can be a uniform raster of terrain heights. The DEM can come from a variety of sources, and they are available at many resolutions. LiDAR is a source for a DEM with high resolution. Appendix A includes an explanation of how LiDAR works. The unique aspect of this tutorial is that it uses a DEM derived from LiDAR, which has better spatial resolution than the MSI, as the input for orthorectification. The use of a DEM derived from Buckeye LiDAR offers advantages over using a more traditional DEM:

1. A DEM derived from Buckeye LiDAR has high resolution that is prepared for the orthorectification of Buckeye imagery, and that often has a spatial resolution in the range of 0.5 to 1.0m. The LiDAR DEM is thus extremely useful for orthorectification because it has better spatial resolution compared to the WorldView-2 commercial satellite MSI used in this tutorial.

2. Buckeye LiDAR is now collected simultaneously along with Buckeye, so there is little temporal discrepancy between the LiDAR DEM and MSI.
3. It is easier to orthorectify Buckeye imagery with Buckeye LiDAR because they are nominally registered together when simultaneously scanning the terrain before the LiDAR cloud is converted to a DEM raster.
4. The accuracy and precision of the LiDAR from Buckeye is very good. The Buckeye LiDAR vertical accuracy with combined systematic and random error is better than 0.5 m.

1.3 Comparing LiDAR DEM and MSI resolutions

Table 1-1 lists the nominal spatial and spectral resolutions between the Buckeye LiDAR DEM and the MSI data that are used to combine both datasets. The high resolution MSI used for this tutorial is WorldView-2. The WorldView-2 imagery contains eight bands and has a spatial resolution or GSD of approximately 2 m. The GSD is defined as the width or length of an image picture element (pixel) projected onto the terrain surface, commonly called a pixel footprint. These are approximate nominal values for the MSI GSD (LANDinfo Worldwide Mapping, 2014; Satellite Imaging Corporation, 2013). However, the actual GSD for each pixel footprint throughout the MSI depends on the terrain heights and on the orientation of the sensor while it scans the terrain. The spectral resolution of MSI is expressed as bands with a range of wavelengths for the measured energy that is incident onto pixels of each layer.

Table 1-1. DEM and WorldView-2 MSI resolutions.

Worldview-2 MSI & LiDAR DEM Resolutions			
WV Band	GSD (meters)	Spectral Wavelength (nanometers)	Color
1	2.0	400-450 nm	coastal
2	2.0	450-510 nm	blue
3	2.0	510-580 nm	green
4	2.0	585-625 nm	yellow
5	2.0	630-690 nm	red
6	2.0	705-745 nm	Red-Edge
7	2.0	770-895 nm	NIR-1
8	2.0	860-1040 nm	NIR-2
WV Pan	0.5	450-800 nm	gray
LiDAR	1.0	Terrain Heights	gray

Many options exist regarding the output spatial resolution GSD in each of the X-East and Y-North directions for the orthoimage. One option uses the default output GSD values provided by the software during the process of making each orthoimage. It is unnecessary to determine another GSD that is common to all separately produced orthoimages. However, the raw MSI still is resampled when producing an orthoimage because of the X-East and Y-North orientation for an orthoimage compared along the X-direction and across the Y-direction of the flight track within the raw MSI space. Appendix B describes other options for the produced orthoimage GSD. Note that this tutorial uses the output GSD for each orthoimage suggested by the software that reflects the nominal spatial resolution of the raw MSI. The tutorial does not use the two optional steps that are mentioned, but not used, in the Chapter 2, “Procedures” (see p 37).

1.4 Methods of orthorectification

1.4.1 General process of orthorectification

The general process of making orthoimages uses a sensor model with projective equations to find the nearest MSI pixel that matches the X , Y , and Z -elevation value from the DEM raster, or, it uses interpolated terrain heights from the DEM raster when there is a mismatch between output orthoimage GSD and the DEM raster GSD. These are commonly called “projective” equations because they describe the sensor line-of-sight when each pixel within its imagery is exposed. These equations, which project from the DEM to the MSI, contain parameters that express the exterior and interior orientations of the sensor when each pixel is exposed.

1.4.2 Sensor models that use RPC

RPC can replace using the actual sensor model to find the MSI pixel that is a function of the X , Y , and Z values from the DEM raster. Appendix C describes the RPC concept in more detail. These RPC are used in place of the actual sensor model with its projective equations that know the exterior and interior orientations for the sensor plus its platform (Forstner, et al., 2013; Hu, et al., 2004; Jacobsen, 2008; Tao & Hu, 2001). WorldView-2 MSI often provides RPC as metadata. RPC can be used when the actual sensor model information is unavailable to the user. It is easier to incorporate a generic RPC replacement sensor model into the image processing software that is making the orthoimages, compared to using the greater complexity and the proprietary content of the actual sensor model. These RPC replace the actual sensor model for ground-to-image transforms with

a single set of parameters for each segment of WorldView-2 MSI. It is possible to use the RPC for producing an orthoimage when there is a DEM in a raster format that covers the same area as the MSI. The entire orthorectification process reduces visible mismatches between overlapping orthoimages regardless of using the RPC or the actual sensor model.

1.4.3 Orthoimage mosaics

The process to create a mosaic of orthoimages ensures that a collection of overlapping adjacent orthorectified image frames cover a larger area, where the seams between them are unseen when the frames are combined into one image. The orthoimage mosaic process is unnecessary if a single orthoimage covers the entire area of interest. Chapter 2 of this tutorial, “Procedures,” describes the whole process of making each orthoimage. Appendix D briefly describes a separate process to combine image frames into an orthoimage mosaic. The process outlined in this tutorial describes two overlapping, but separately produced orthoimages. This tutorial ignores tonal imbalance and output GSD discrepancies between orthoimages in a mosaic. Two remaining concerns that will be addressed in future efforts are: (1) Many customers, including those doing MSI feature extraction from the orthoimages, consider it unacceptable when the tonal imbalance forms a “quilted patchwork” in the orthoimage mosaic, and (2) The mosaic of orthoimages with different GSD can be problematic.

1.4.4 Tutorial software

Except for a process where the LiDAR point cloud is converted to a DEM raster by software, this tutorial also uses a single image processing product and it does not combine results from more than one software package. This tutorial produces orthoimages solely with *ERDAS Imagine 2011* commercial imagery processing software, which can process the National Imagery Transmission Format (NITF) with an RPC sensor model when making the orthoimages using a DEM raster. NITF is a standard that provides a detailed description of the overall file structures for formatting and exchanging digital imagery. The NITF contains supporting metadata to describe the image data and the products related to it (NITF Standard Technical Board, 2007). Other commercial imagery processing software can produce orthoimages, but their processing steps might vary slightly from what is described in this tutorial when commercial satellite MSI exists with RPC, for example, WorldView-2 in the NITF. Nevertheless, the processing steps described here can be adapted to other imagery processing systems that contain the RPC sensor model.

2 Procedures

2.1 Summary

This chapter describes the steps necessary for making an orthoimage with a LiDAR DEM raster and the RPC sensor model that comes with WorldView-2 MSI. The steps outlined here suggest the processing steps for making orthoimages from other DEM and MSI data besides LiDAR and WorldView-2, if RPC come with the MSI. From this process, it is also possible to extrapolate general procedures needed to create orthoimages using commercial image processing software besides *ERDAS Imagine 2011*.

Figure 2-1 shows the start-to-finish production flowchart of the main processes to create an orthoimage with the LiDAR DEM raster and the Worldview-2 commercial satellite MSI, after the single mosaic for the entire set of LiDAR DEM raster tiles has been formed. Equation 2-1, which uses the notation shown in Figure 2-1, denotes how the brightness value (b_i) for an orthoimage grid-cell from the nearest pixel is found in each MSI layer- i by the sensor model (\rightarrow):

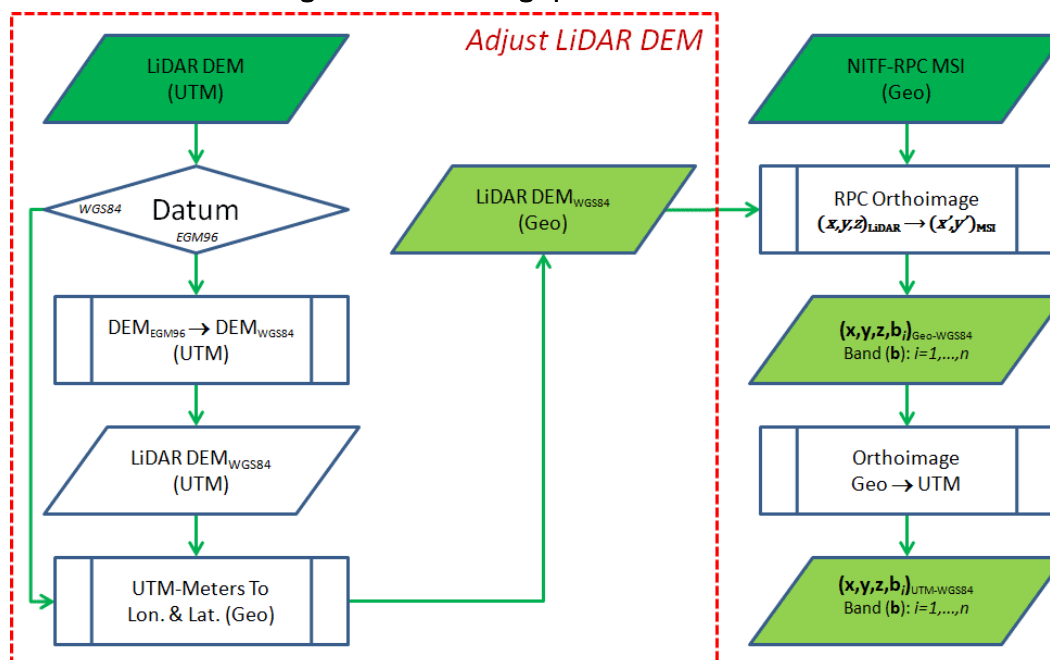
$$(x, y, z, b_i)_{Geo-WGS84} = (x, y, z)_{LiDAR} \rightarrow (x', y', b_i)_{MSI} \quad (2-1)$$

Appendix C details the photogrammetry mathematics and projective equations of the sensor model. The remaining sections in this chapter contain information and stepped processes for making an orthoimage.

Section 2.2 describes the suggested file structure of the LiDAR DEM raster, and of the MSI, for the processing described in this tutorial.

Section 2.3 describes how to load the DEM and MSI into the *ERDAS Imagine* viewer for inexperienced image processing software users. The instructions for subsequent subsections presume that the user can load data into the viewer to keep track of processing results. Note that many steps can be applied without the images loaded into the viewer. When images must be loaded into the viewer to complete subsequent processing steps, an additional “Load ... image into viewer” step will be added to each set of instructions.

Figure 2-1. Orthoimage production flowchart.



Section 2.5 describes how to combine separate LiDAR DEM raster tiles into one mosaic because the image processing software and the production flowchart presumes that there is a single DEM raster that covers the entire ground footprint of each MSI frame.

Section 2.6 describes the “Adjust LiDAR DEM” process to shift the entire DEM raster mosaic of its UTM terrain height values from the Earth Gravity Model 1996 (EGM96) datum* into the World Geodetic System 1984.† Note that the software incorrectly interprets LiDAR DEM datum as WGS84 instead of EGM96. This misperception must be corrected by adjusting the terrain height values in the DEM raster. Appendix E includes an example that shows why the terrain height values within the DEM raster should be converted from the EGM96 to the WGS84 datum expected by the RPC for the MSI, because large differences in respective terrain height values between the two datums can propagate errors during orthorectification.

*EGM96 refers to the equipotential gravity field depicting mean-sea-level across the Earth that is commonly called the geoid.

†WGS84 refers to an earth-centered ellipsoid of revolution coordinate system for projective equations to satellites.

Section 2.7 describes transformation of the UTM projection, with its adjusted terrain height values, to the projection of geographic longitude and latitude decimal degrees expected by the RPC sensor model.

Section 2.8 completes the process of creating the orthoimage from the converted LiDAR DEM raster and from the raw MSI with the RPC sensor model.

Section 2.9 describes the process to project the produced orthoimage from geographic longitude and latitude decimal degrees into a desired coordinate system for example UTM meters, which was the same projection of the original LiDAR DEM raster. The mosaic process for the separately produced orthoimages is very similar to the process of merging multiple LiDAR DEM tiles into one piece. Appendix D describes the orthoimage mosaic process as similar to that for the DEM raster, so the same process may be used to create a mosaic of orthimages with different GSD resolutions.

2.2 Description of DEM and MSI data

Figure 2-2 shows the *ERDAS Imagine* viewer containing the NITF with RPC for two overlapping frames of the WorldView-2 8-band commercial satellite MSI. The LiDAR DEM is underneath the shown MSI. These LiDAR DEM raster tiles and MSI data are the material used in this tutorial. The quilted patchwork texture that characterizes the image of the LiDAR terrain heights grids will disappear when the frames are joined into a single mosaic of the elevations. The shape of every LiDAR DEM raster tile that spans the same area as the MSI frames is shown with a blue outline.

The preparation of the LiDAR DEM raster is the most complex aspect of making the orthoimage. To get correct results, the LiDAR must be converted to the same format and content expected by the MSI RPC, including its projection plus horizontal and vertical datum.* This tutorial explains how to do that next.

* For help in gathering the DEM from LiDAR, or in gathering commercial satellite MSI with RPC to conduct the process of making orthoimages, contact Roger.O.Brown@usace.army.mil

Figure 2-2. LiDAR terrain heights elevation grids beneath WorldView-2 MSI.

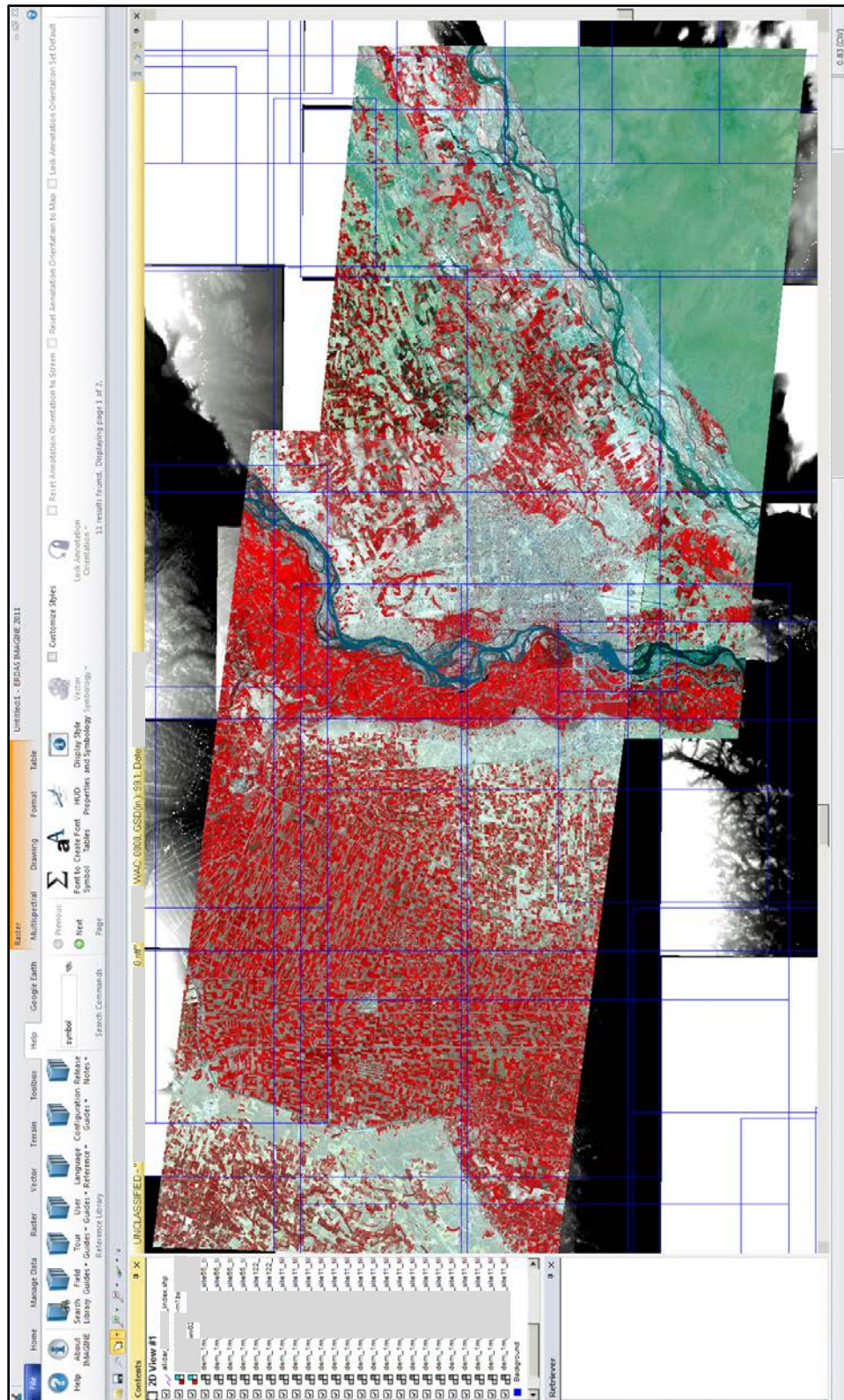


Figure 2-3 shows the recommended file/folder organization for this task:

- The “LiDAR” folder contains the LiDAR DEM rasters.
- The “WV2_” and “WV2_” folders each contain one of the two overlapping MSI frames.
- The “_LiDAR_MSI.ixs” file and the “_LiDAR_MSI” folder contain data that describe the *ERDAS Imagine* “session” shown in Figure 2-2.
- The “_LIDAR_IFSAR_IndexShapes_15Dec11” folder contains the shapes of the boxes with blue outlines in the viewer.

Figure 2-3. DEM and MSI folder plus files data structure.

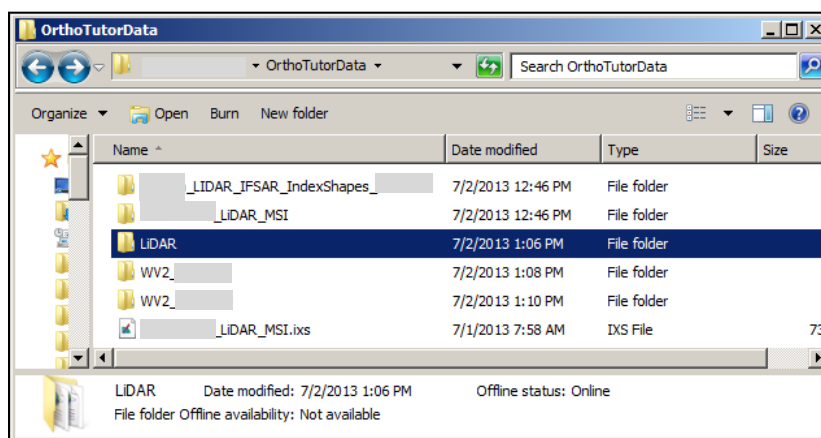


Figure 2-4 shows the LiDAR DEM raster files contained in the “LiDAR” folder. Note that the “_a1_” in each “*.tif” filename indicates that these files contain terrain heights from the first return of the LiDAR.

Figure 2-5 shows the MSI files contained in the “WV2_” folder, in which the “*.ntf” file contains the MSI raster highlighted with a blue background. Other files in this folder contain metadata (including RPC) that support further processing of the MSI to create its orthoimage. The “WV2_” folder contains similar data for the second MSI frame used in this tutorial.

Figure 2-6 shows the geometric mismatch between a pair of WorldView-2 MSI frames used in this tutorial, each of which is exposed one day apart. This tutorial describes the construction of the northwest orthoimage. The southeast orthoimage shown in later figures was made by using the same process use to create the northwest orthoimage. Figure 2-7 shows that most of the image mismatch between the two raw MSI (e.g., along the dotted red line) is removed after making each orthoimage separately.

Figure 2-4. LiDAR DEM raster files (*.tif).

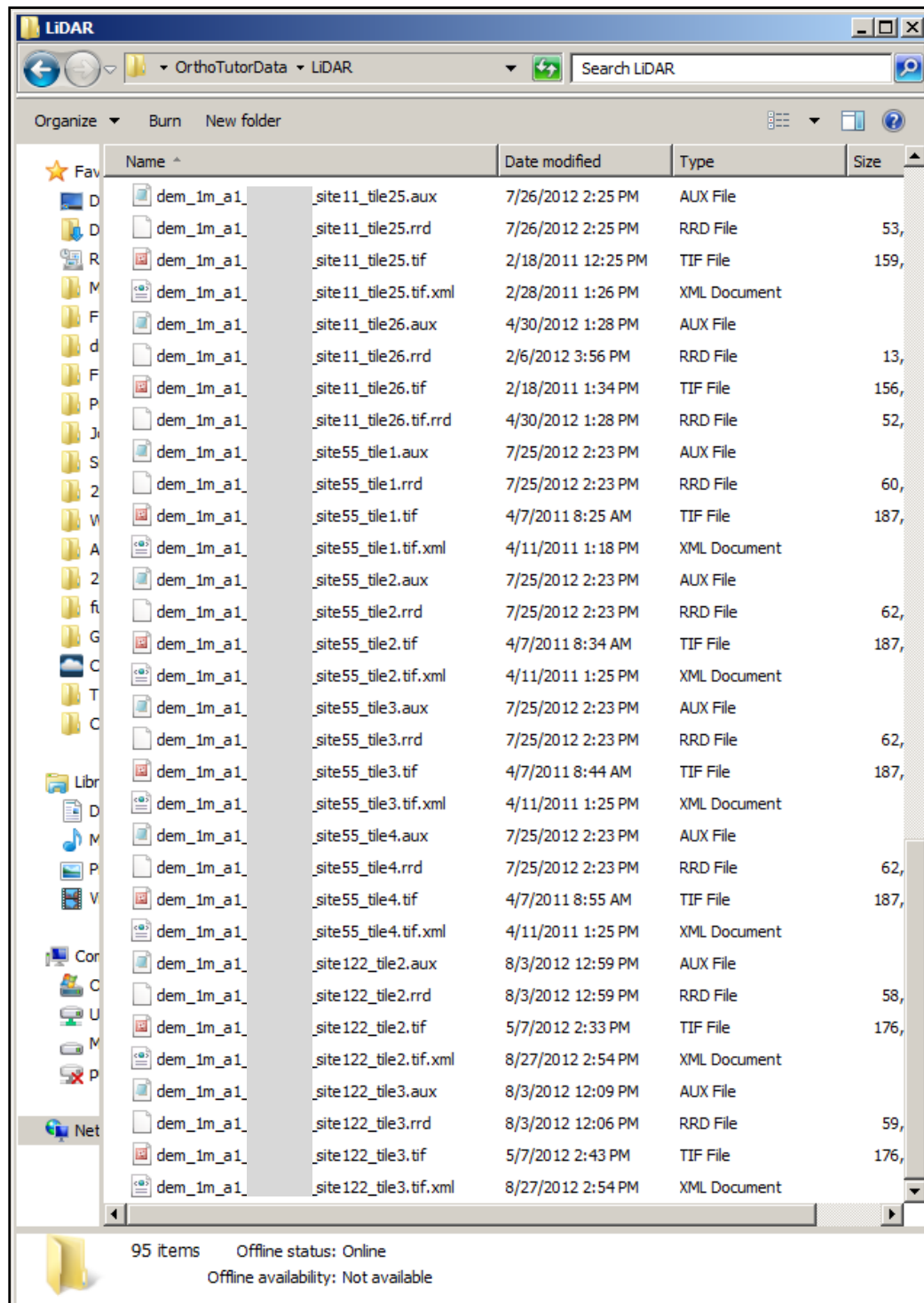


Figure 2-5. MSI files (*.ntf).

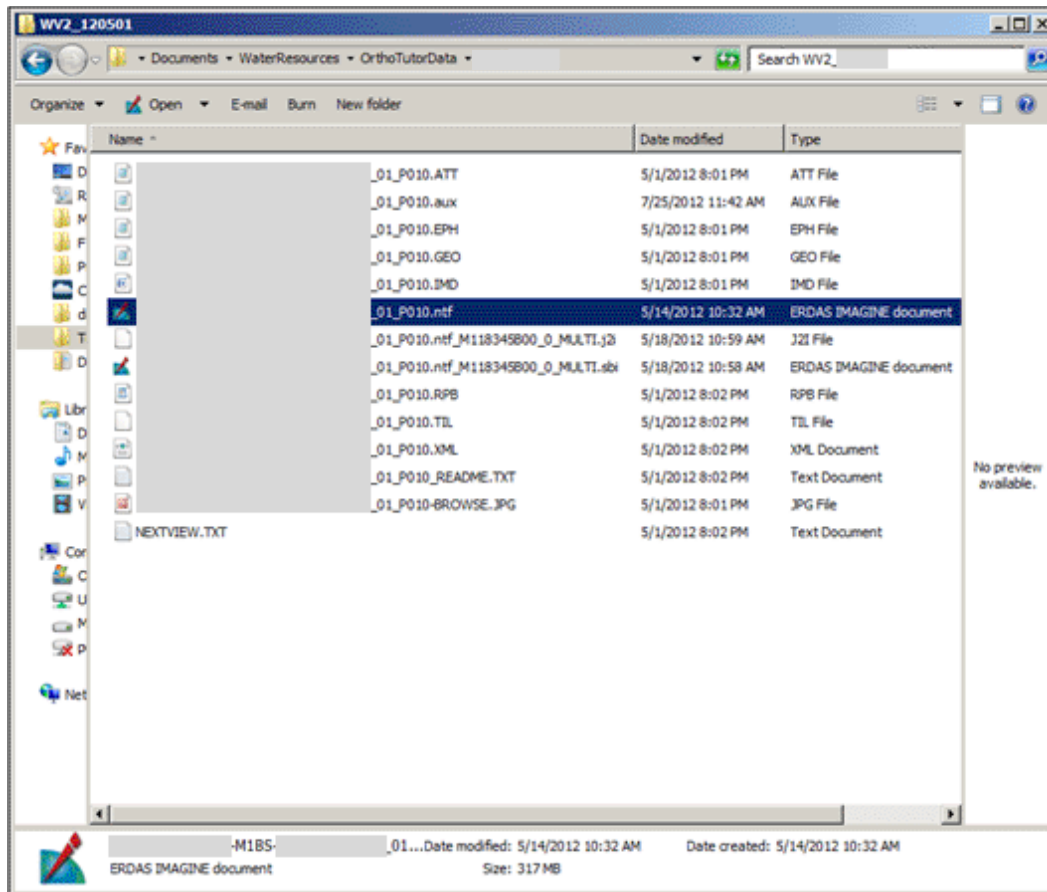
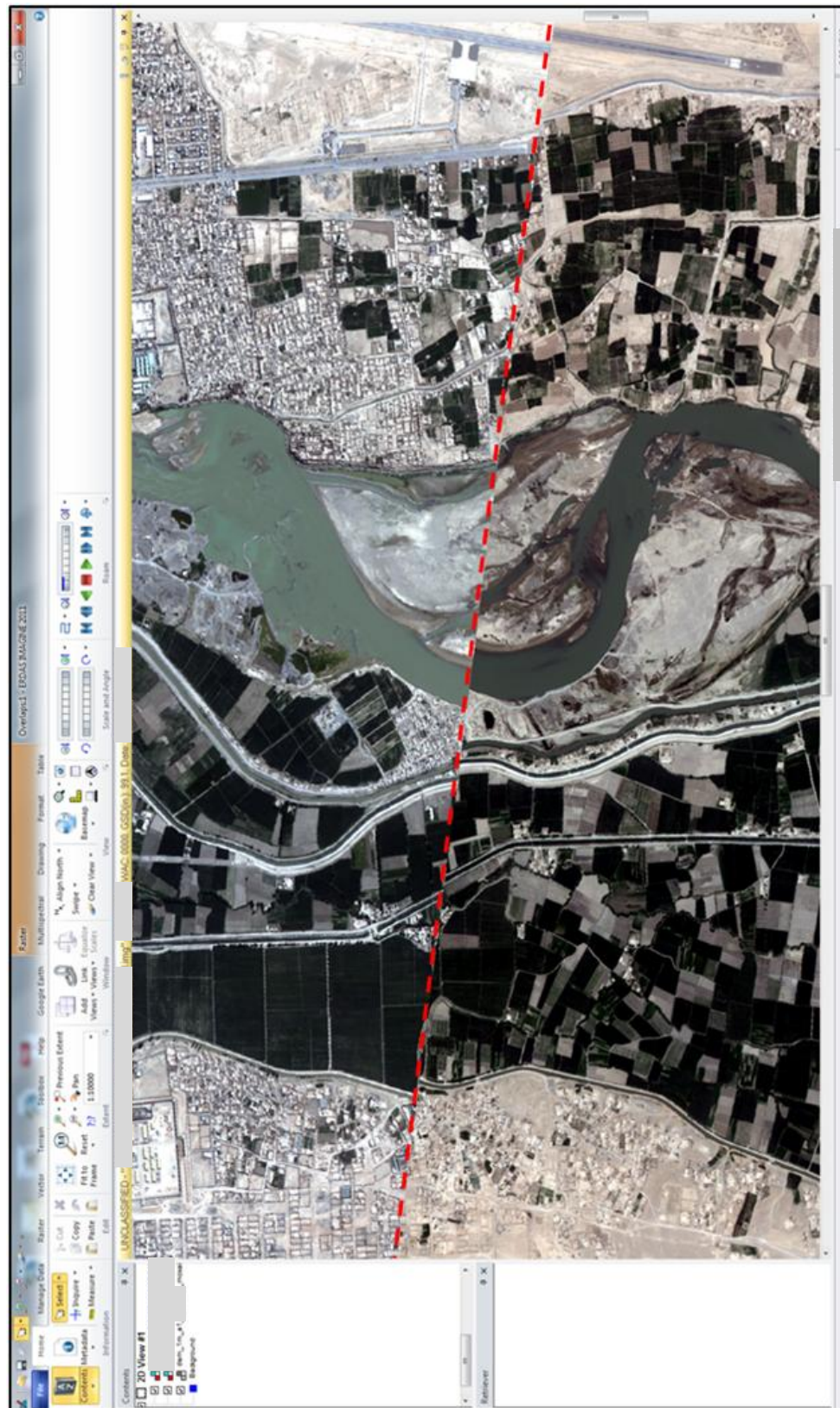


Figure 2-6. WorldView-2 image frames mismatch before making orthoimages.



However, some geometric and spectral discrepancies remain after orthorectification. Removing these remaining geometric discrepancies, including tonal imbalance between both orthoimages, is a subject for future research. Although this chapter does not explain the process for forming the mosaic from separately produced orthoimages, it is similar to the steps taken to form the LiDAR DEM mosaic described in Section 2.5. Future basic or applied research should explore a method to remove the remaining spatial and spectral discrepancies that remain in the displayed overlapping orthoimages. Nevertheless, apparent spatial mismatch that remains after making each orthoimage should still be less noticeable than that seen between each overlapping frame of separate raw MSI frames before their conversion to orthoimages.

2.3 Tutorial overview

This tutorial presumes that most users know how to load the DEM raster and MSI data into the *ERDAS Imagine* viewer. Most image processing steps can be applied without the data loaded into the viewer. Consequently, the instructions beyond Section 2-4 do not include the steps for loading the data into the viewer, unless a “Load ... into the viewer” step is required. The user is advised to use the viewer to review the image processing results before taking subsequent steps to ensure that the process has produced the desired results.

This following tutorial takes the form of a series of hands-on, three-part exercises:

1. The short paragraph that begins the exercise explains the overall intent of the following stepped exercise. The user is advised to read this introductory material before beginning the steps.
2. Each process is divided into numbered sequential steps.
3. The numbered steps are followed by figures that show the user how to manipulate the software graphic user interface to follow each process. Each numbered step is repeated in the figures to clearly show where the user should take the indicated action.

2.4 Viewing DEM and MSI data

Figures 2-7 through 2-13 (Steps 1-8) show how to load a DEM Tagged Image File Format (TIFF) raster frame into the *ERDAS Imagine* viewer. To load the MSI NITF into the viewer, repeat Steps 1-8, but this time, in Step 5, pick “NITF 2.x.” These steps also apply to viewing other DEM

raster tiles and MSI frames. Presume that “press” or “select” means to click the button on the left-hand side of the mouse. “Press-RHMB” means click the button on right-hand side of the mouse that is a less frequent action. The terms “press” or “select” were used in case the computer has a touchscreen that you “tap” instead of the “click” of a mouse button. The “Press-RHMB” instruction might be another action on a touchscreen.

1. Select “2D View #1” in the “Contents” subframe to open the dropdown list.
2. Select the “Open Raster Layer..” item from dropdown list.
3. Type the pathname into the “File name:” field of the “Select Layer to Add:” menu.
4. Press button at right side of “Files of type:” dropdown to view the list.
5. Select “TIFF” from the file type list.
6. Select the filename of the desired image from the “Select Layer to Add:” menu, then press “OK.”
7. Press-RHMB to select the filename in the “Contents” subframe to view the popup list.
8. Select “Fit Layer To Window” from the popup list.

Figure 2-7. Open raster layer into viewer.

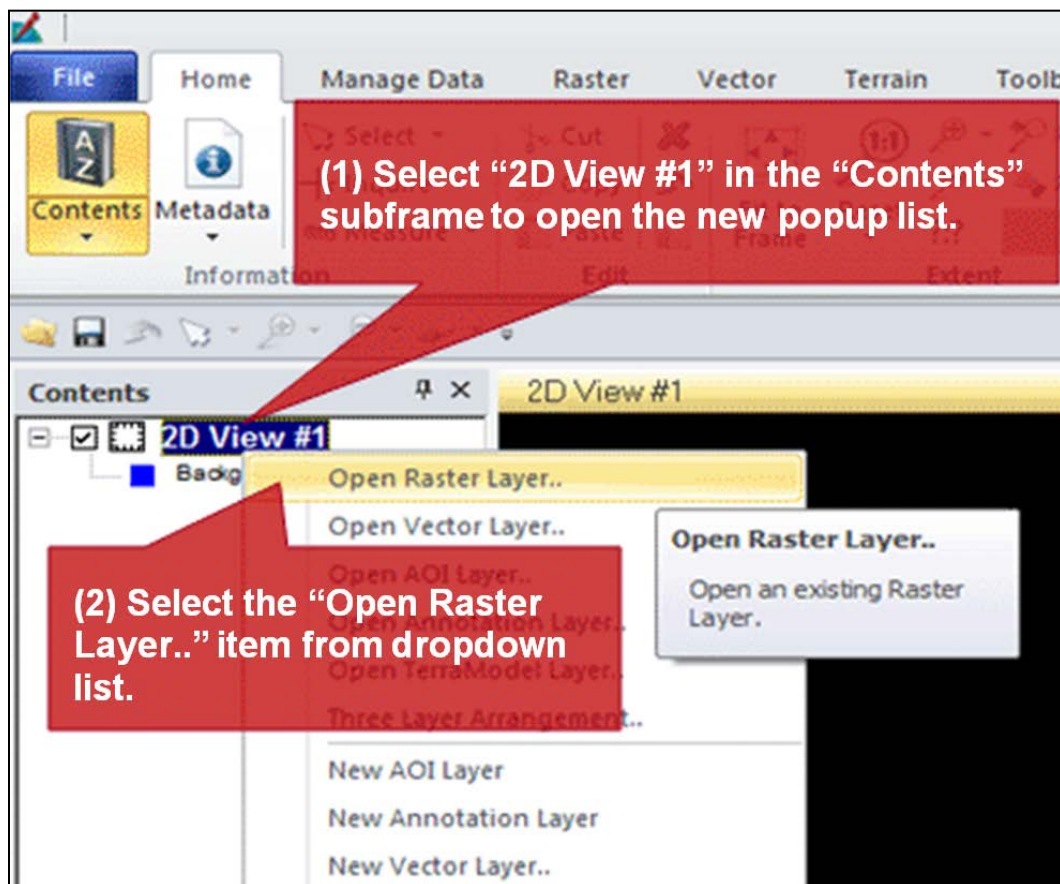


Figure 2-8. Show pathname for layer to add.

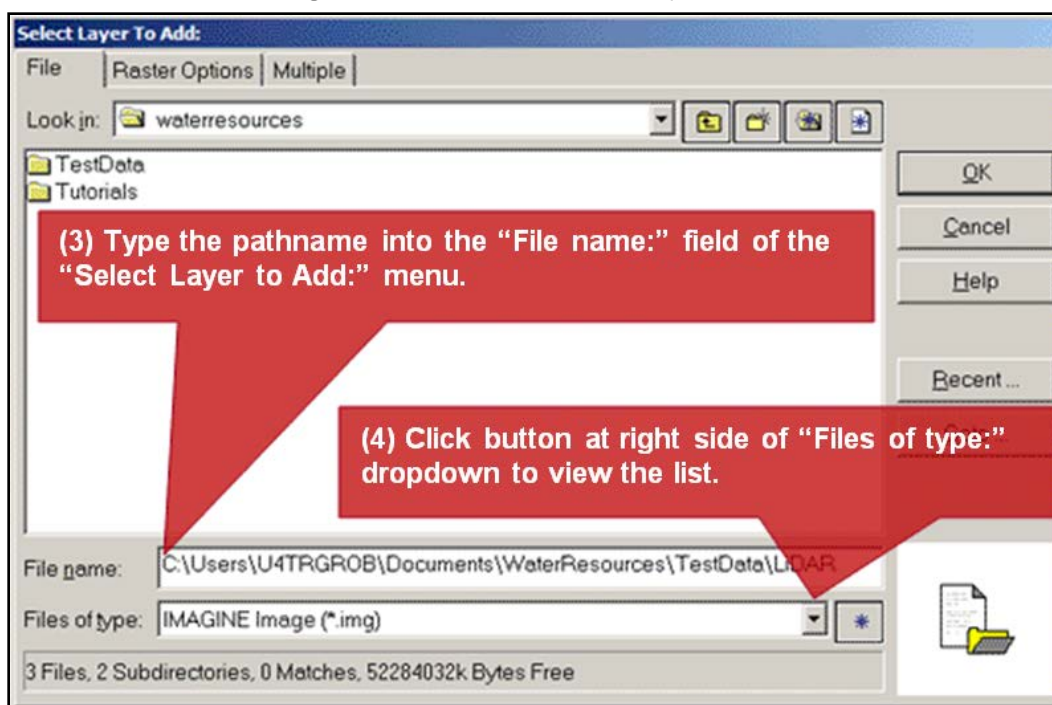


Figure 2-9. Select layer to add.

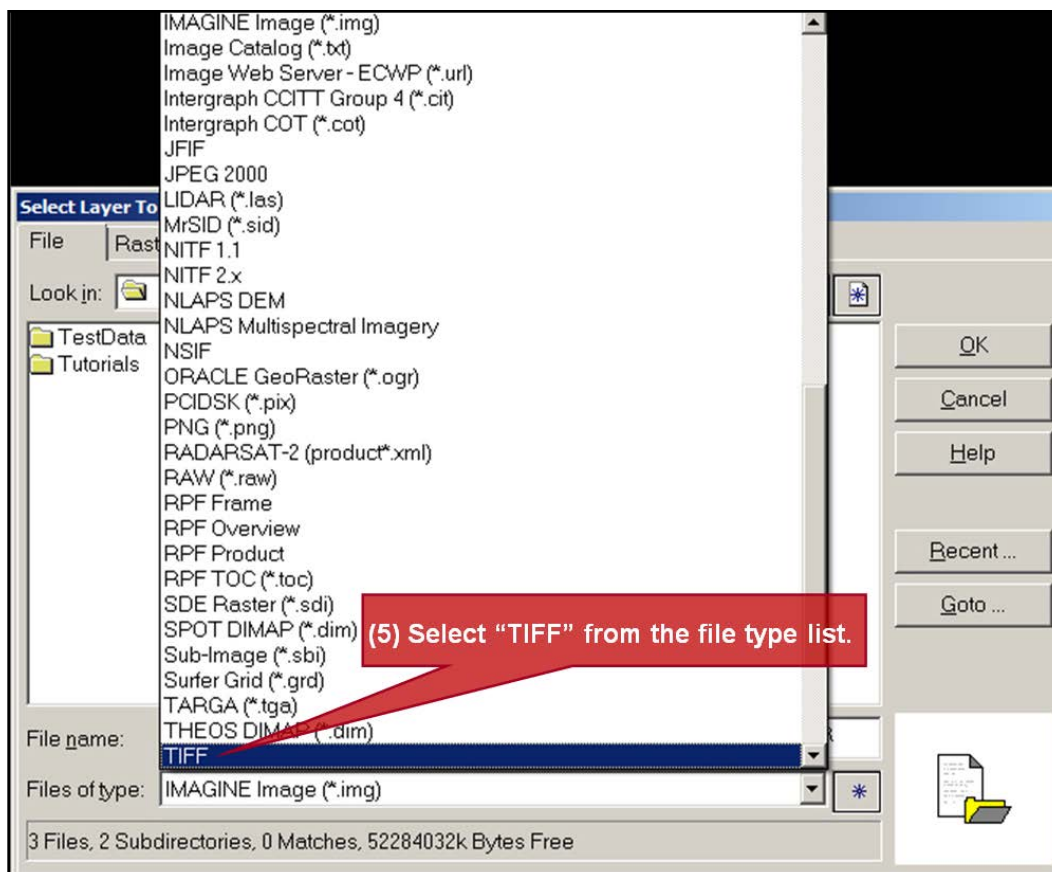


Figure 2-10. Pick image frame to view.

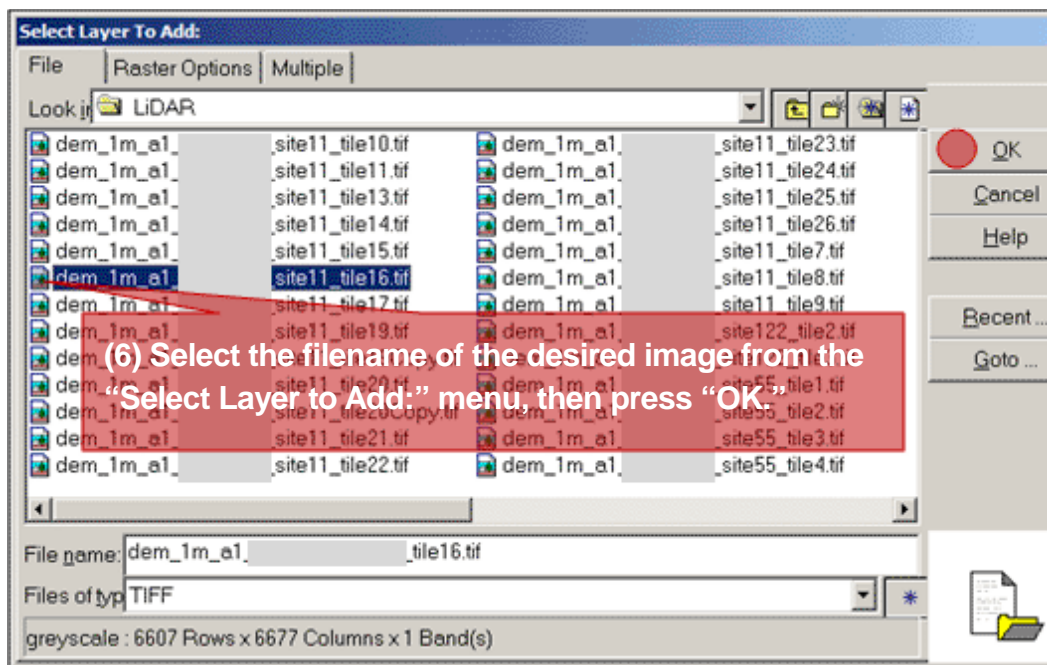


Figure 2-11. Fit entire image into viewer.

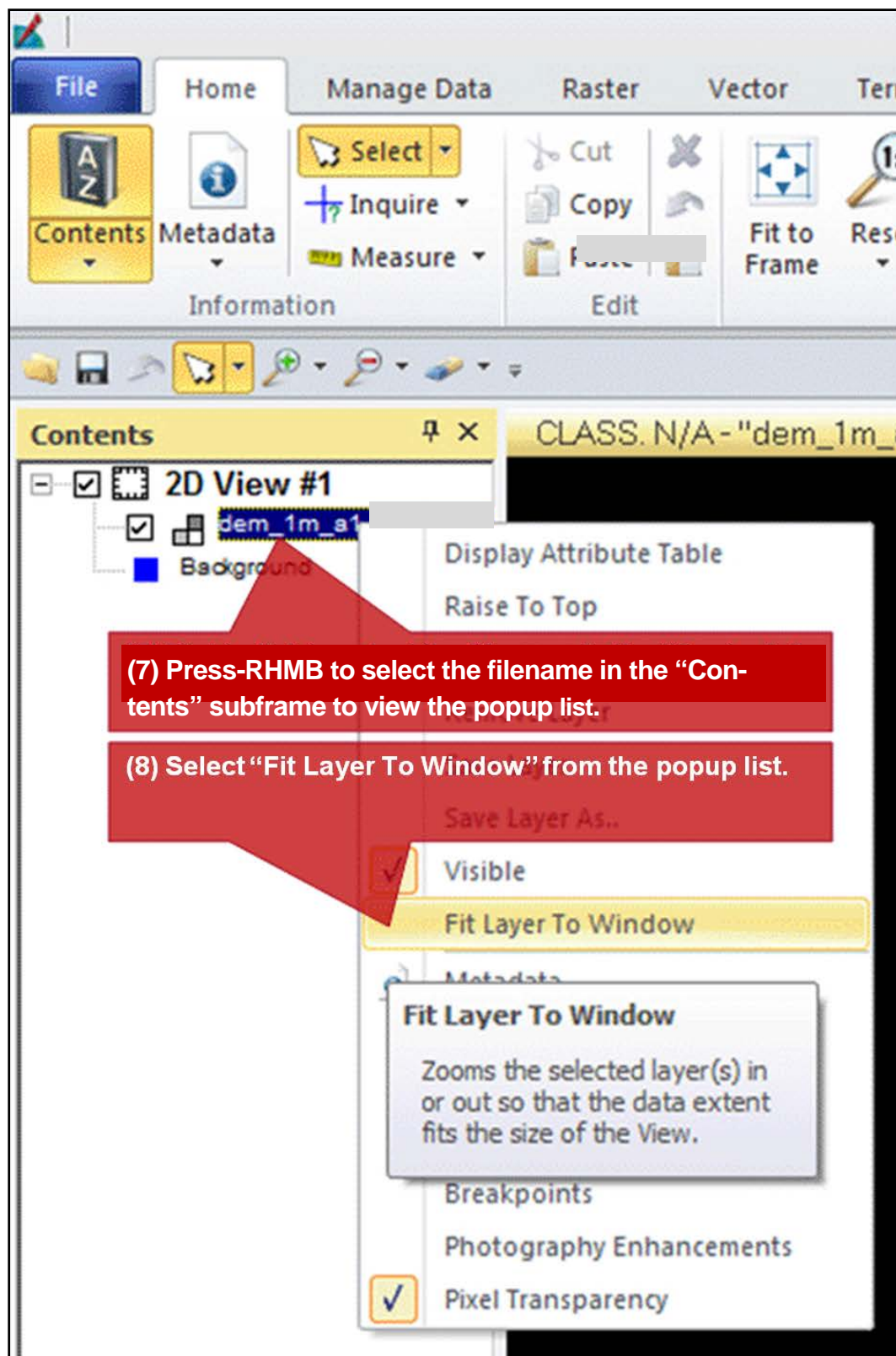


Figure 2-12 shows the LiDAR DEM raster fit to the viewer window, in which lighter pixels indicate higher terrain heights.

Figure 2-12. Entire image fit into viewer.

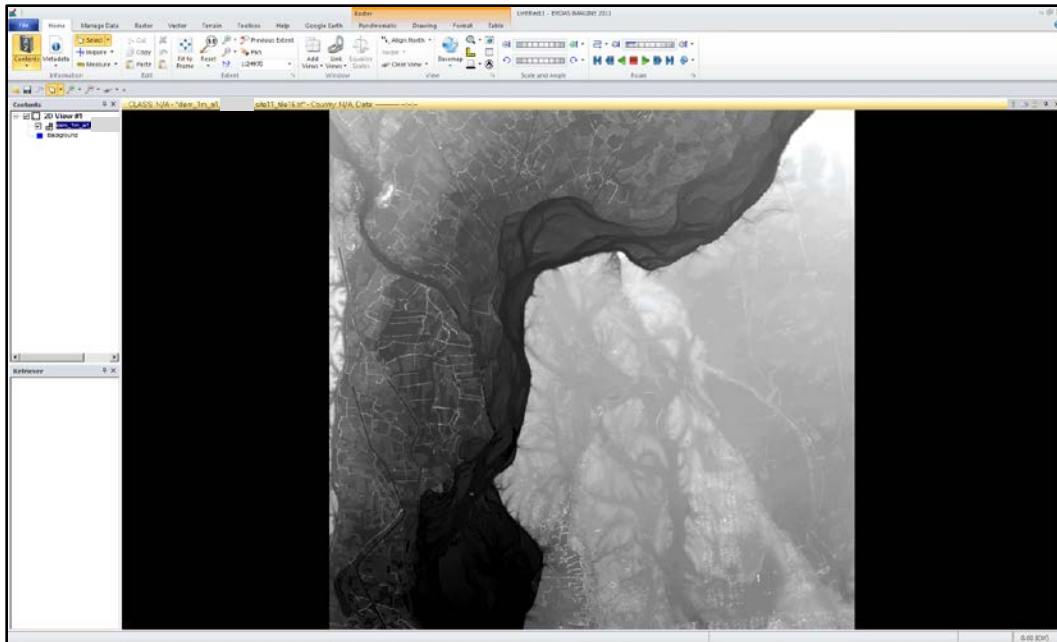


Figure 2-13 shows the results of repeating Steps 1-8 to load the MSI NITF into the viewer. Presuming the same file and folder structures mentioned in Section 2.3, type:

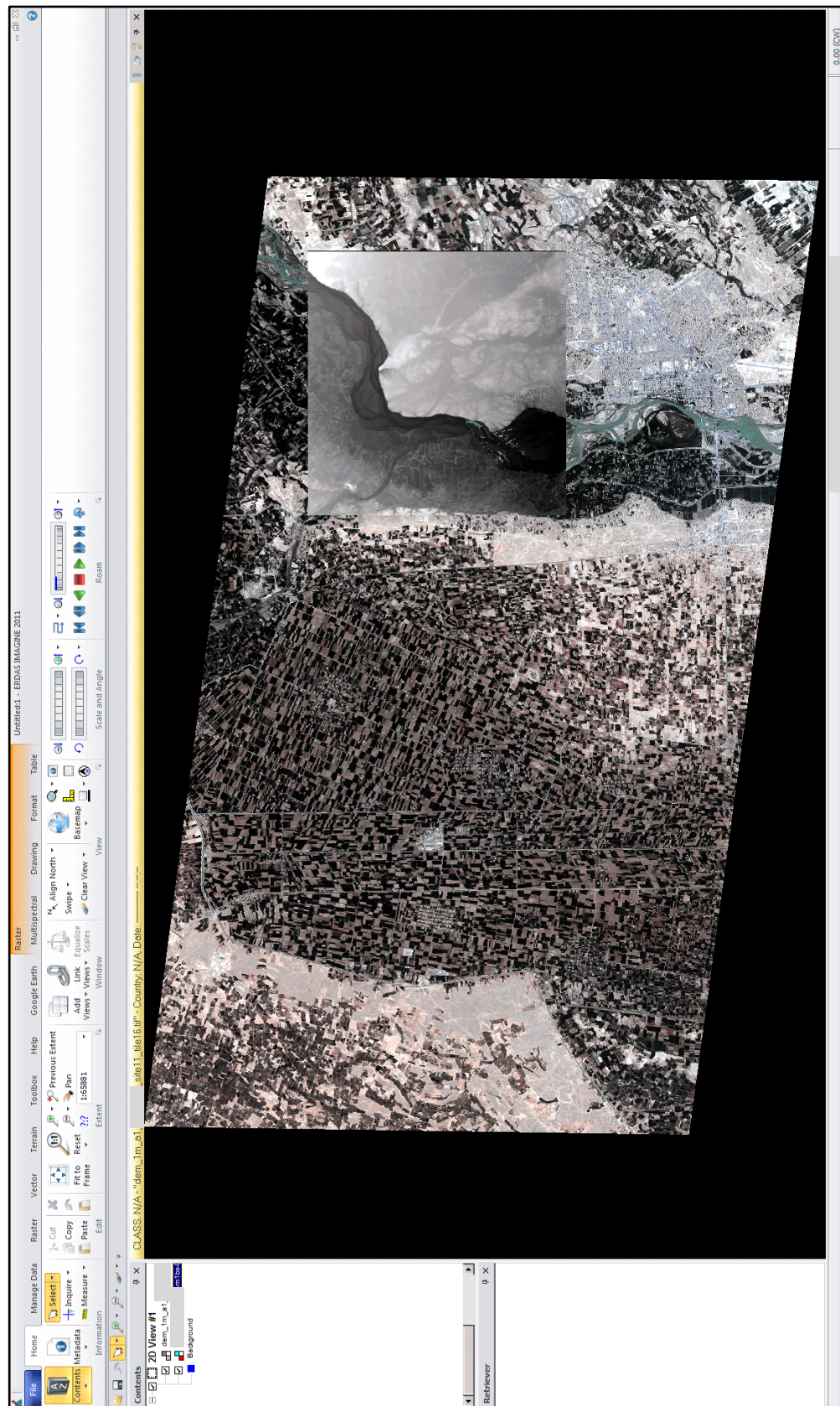
C:\Users\U4TRGROB\Documents\WaterResources\TestData\WV2

for the pathname in Step 3. Press “NITF 2.x” instead of “TIFF” in Steps 4-5 to find the:

-M1BS- _01_P010.ntf

filename in Step 6. Drag the DEM filename above the MSI filename into the Contents subframe, after loading MSI into the viewer, and then fit the MSI to the viewer window to get view shown in Figure 2-13.

Figure 2-13. DEM and MSI View.



2.5 Mosaic LiDAR DEM

Figures 2-14 through 2-16 show the process used to join the LiDAR DEM grids into a single mosaic. Steps 1-5 initially populate the list of grids that are part of the terrain heights mosaic. The viewer will show the LiDAR DEM tiles (although it is not necessary to use the viewer to make the mosaic). Note that the “results found” field is filled in the “Help” tab next to the “Search Commands” field. It is automatically filled with the buttons found from Step 1, and then the box for Step 2 in a figure points to the “MosaicPro” button that is pressed.

1. In the “Help” tab, type “mosaic” into the “Search Commands” field, then press “[Enter].”
2. In the “Help” tab, go to the “results found” group, then press the “Mosaic Pro” button.
3. From the “MosaicPro (No File)” menu, Press “Edit,” then select “Add Images ...” from the dropdown.
4. In the “File name:” field of the “Add Images” menu, type “*.tif” then press “[Enter].” In the same field, type a pathname, then press [Enter].
5. Select the desired filenames from the “File Chooser” menu, then press “OK.”

Figure 2-14. Begin mosaic of LiDAR DEM raster.

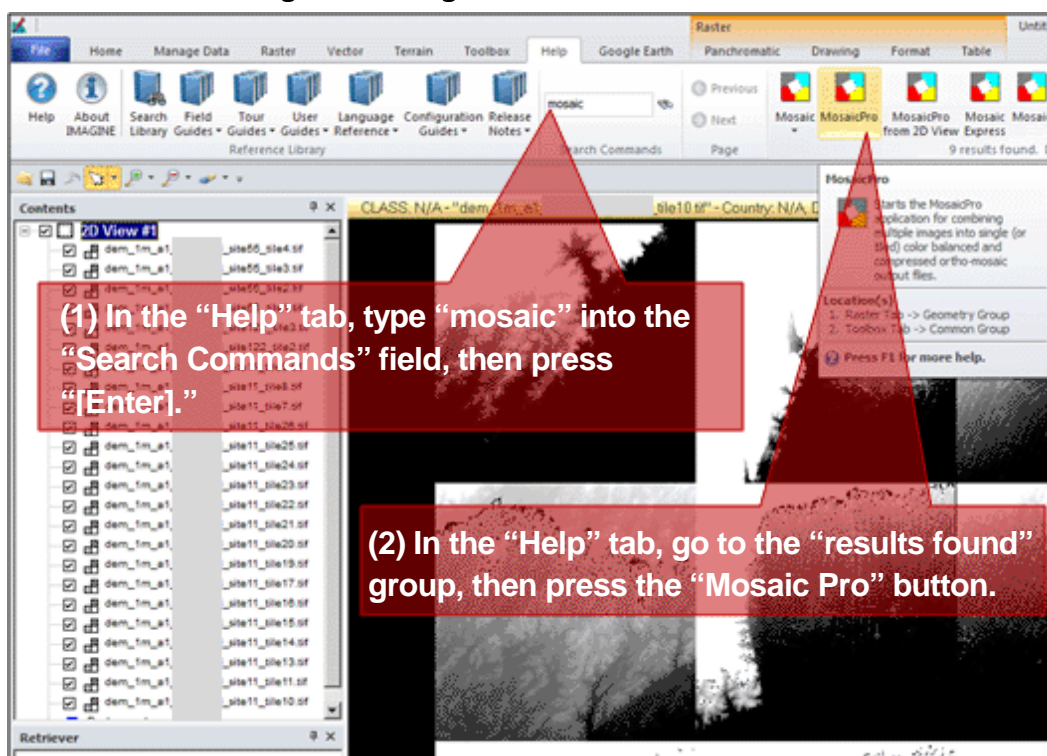


Figure 2-15. MosaicPro “Add Images...”

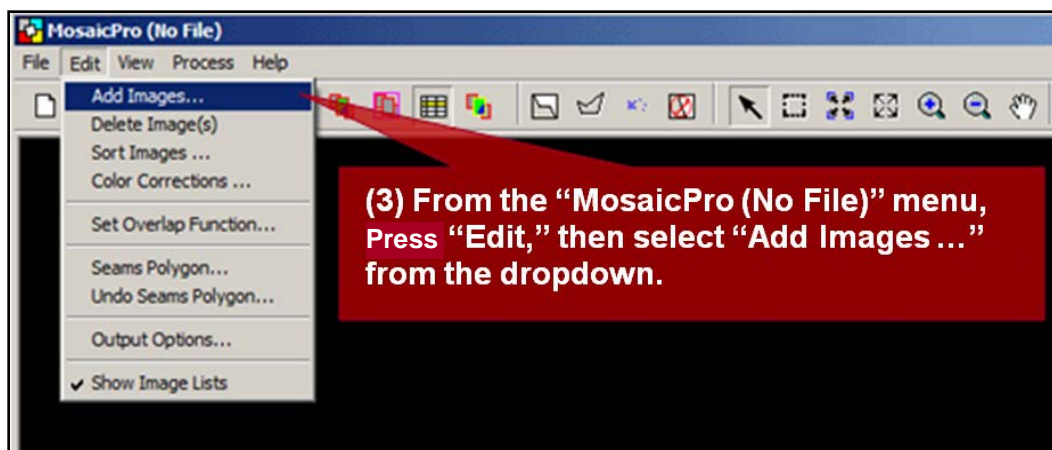
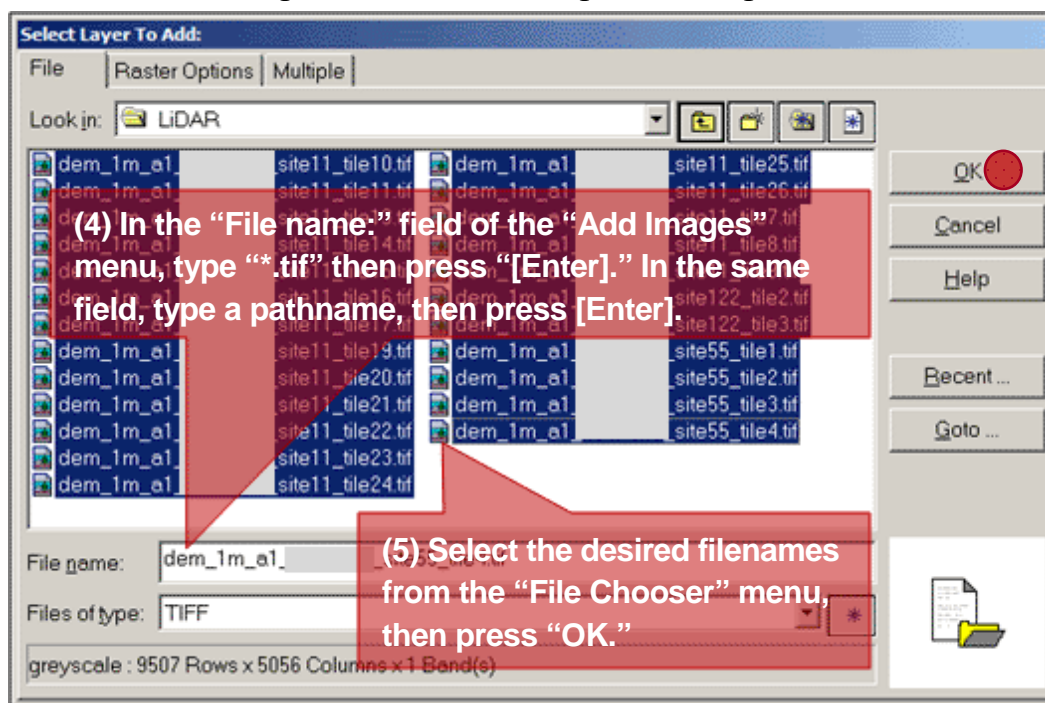


Figure 2-16. Pick terrain heights elevation grids.



Figures 2-17 through 2-20 (Steps 6-7) show how to push an elevation grid to the bottom of the list of "Image Names" that are shown at the bottom subframe of the "Mosaic Pro" menu. Take these steps to ensure using terrain heights of an elevation grid tile in areas where it overlaps other DEM raster tiles. This is helpful, for example, to move tiles in the list so that most recent terrain height values are put in the mosaic. Figures 2-18 through 2-20 (Steps 8-11) show how to run the LiDAR DEM terrain heights mosaic, and Step 12 closes the Figure 2-17 menu.

6. Select a filename to move the tile within the “Image Name” list (repeat steps 6-7 for each tile moved in the list).
7. Press the “Send Selected Image(s) to Top” button.
8. From the (No files)” menu, click “Process,” then select “Run Mosaic ...”
9. In the “Output File Name” popup menu, type the output filename into the “File name” field.
10. Press the “OK” button from the “Output Filename Menu” menu to run the mosaic process.
11. After the “Process List” popup shows the “DONE” state indicating that the mosaic is complete, press “Close.”
12. Once the mosaic process completes, close the “Mosaic Pro” menu by pressing the “X” button in its upper right-hand corner of the menu. (This step not shown within a figure, but it applies to Figure 2-17.)

Figure 2-17. Restack terrain height elevation grid tiles.

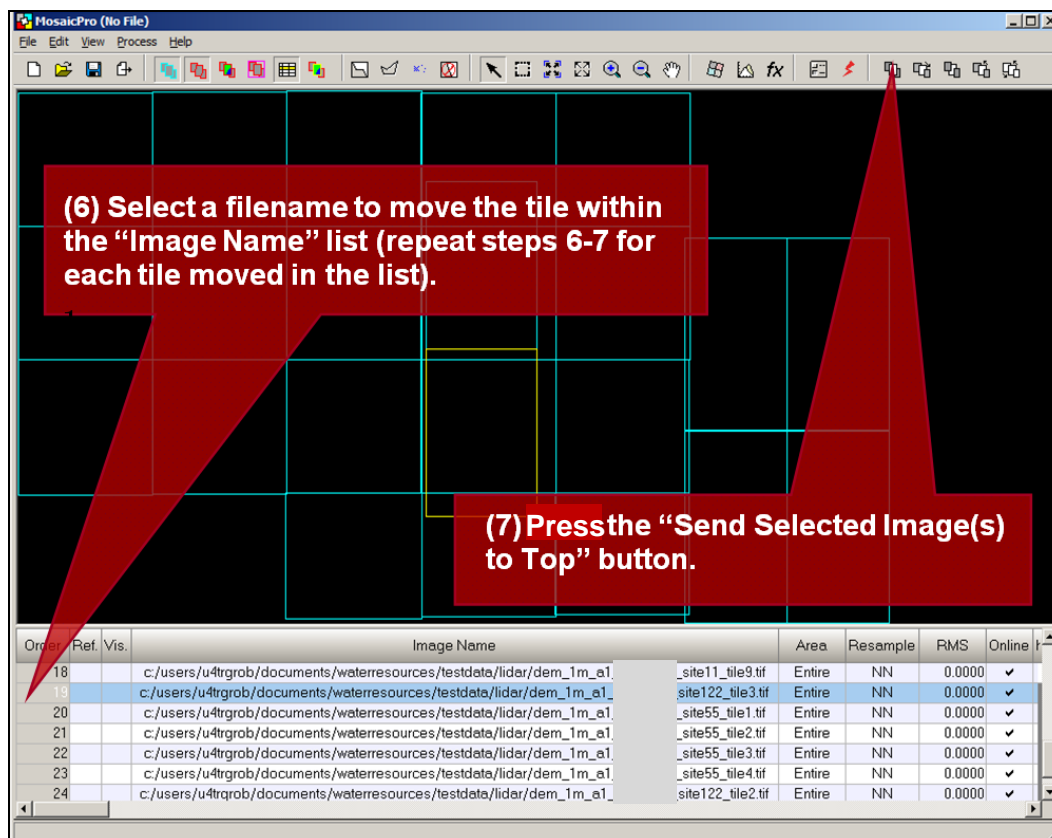


Figure 2-18. Run mosaic process.

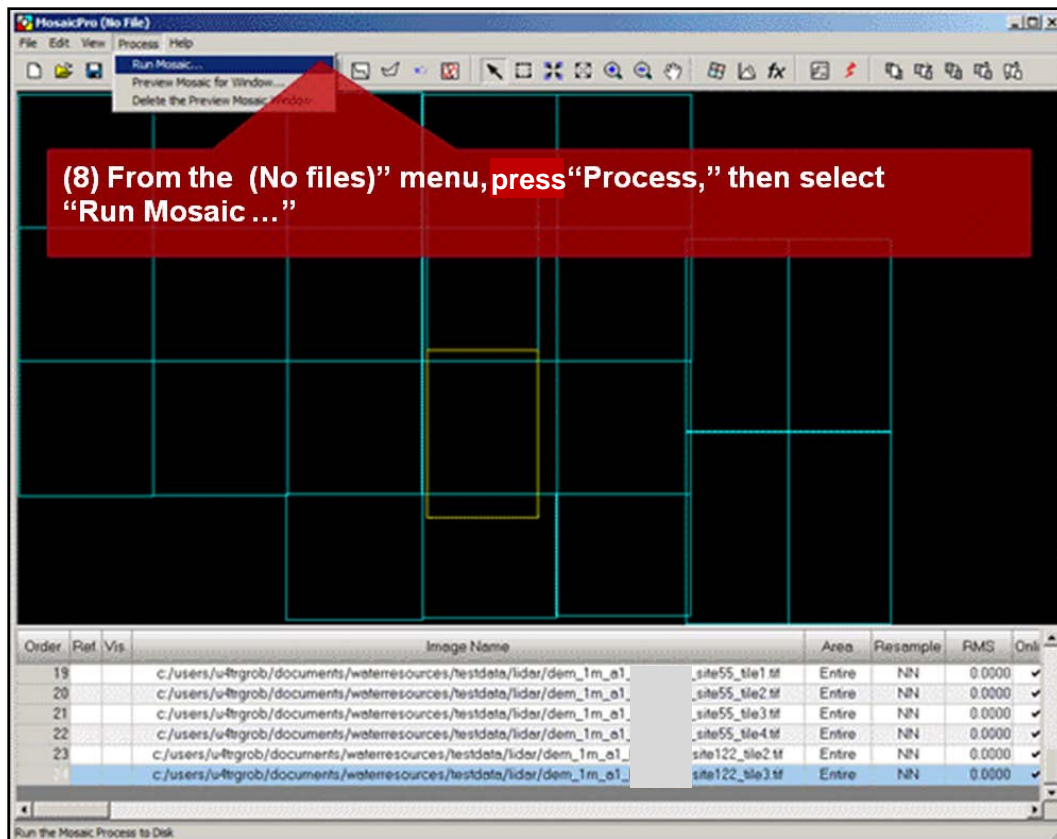


Figure 2-19. Show output filename from mosaic process.

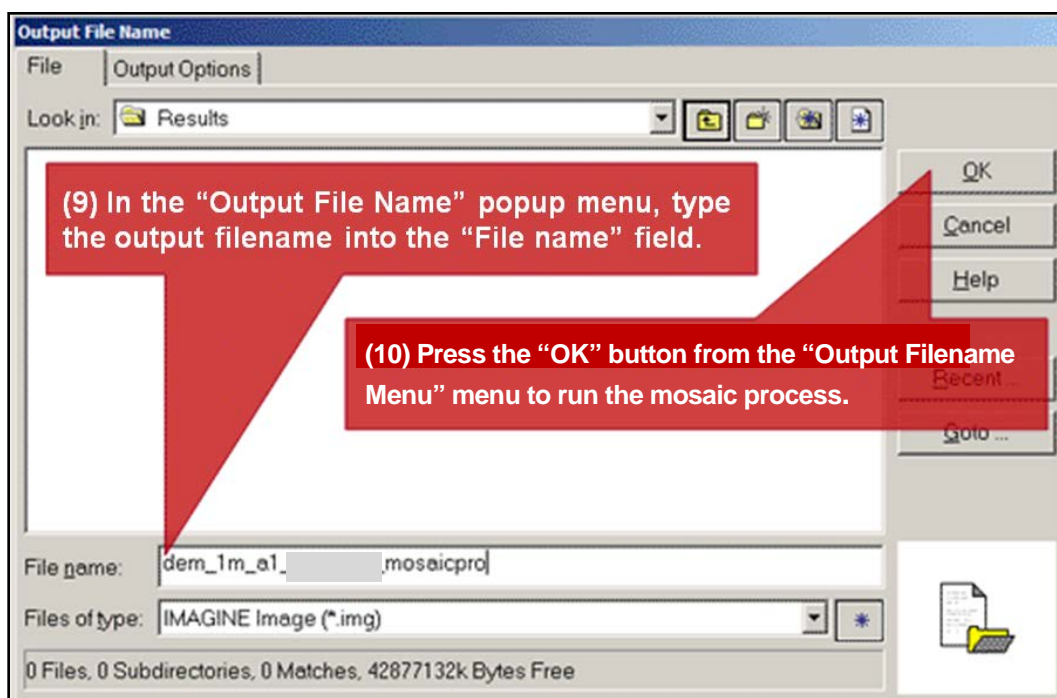
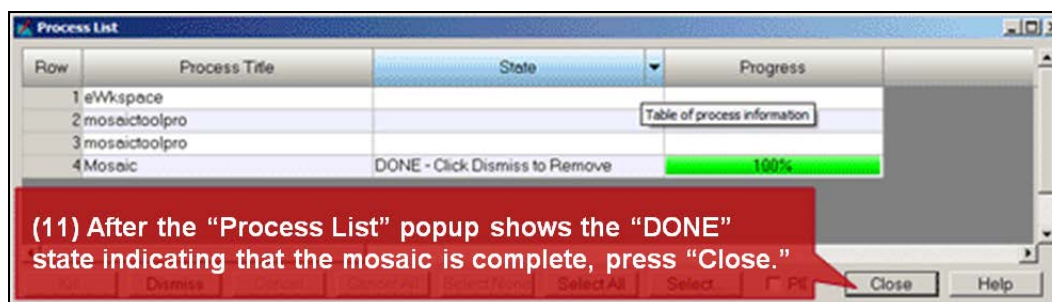


Figure 2-20. Process list mosaic completion.



2.6 Adjust the terrain heights from the LiDAR DEM

Figures 2-21 through 2-23 show the LiDAR DEM raster mosaic of terrain heights that must be converted into geographic latitude and longitude units of decimal degrees, which are the units expected by the WorldView-2 NTF with RPC. Buckeye LiDAR DEM rasters have a UTM projection with horizontal and vertical units of meters. The DEM raster in UTM meters will produce inaccurate orthoimages unless they are converted to the projection and datum expected by the WorldView-2 NTF with RPC first by using the following steps. (Step 1 presumes that you already know how to load images into the viewer.) The *ERDAS Imagine* image processing software incorrectly assumes that the LiDAR datum is WGS84, where it actually is EGM96. Steps 4-5 correct this misperception about the data projection.

1. Load image of LiDAR DEM raster mosaic into the viewer.
2. Select the filename for the LiDAR DEM in the “Contents” subframe, then press-RHMB for the selection to invoke the popup menu.
3. From the same popup menu, click “Metadata” button to invoke the “Image Metadata” menu.
4. To change the incorrect WGS84 datum selection to EGM96Press, select “Add/Change Elevation Info.”
5. From the “Datum Name” dropdown field, select “World Wide 15-Minute Geoid (EGM96)” datum, then press “OK.”

Figure 2-21. LiDAR terrain heights elevation mosaic.

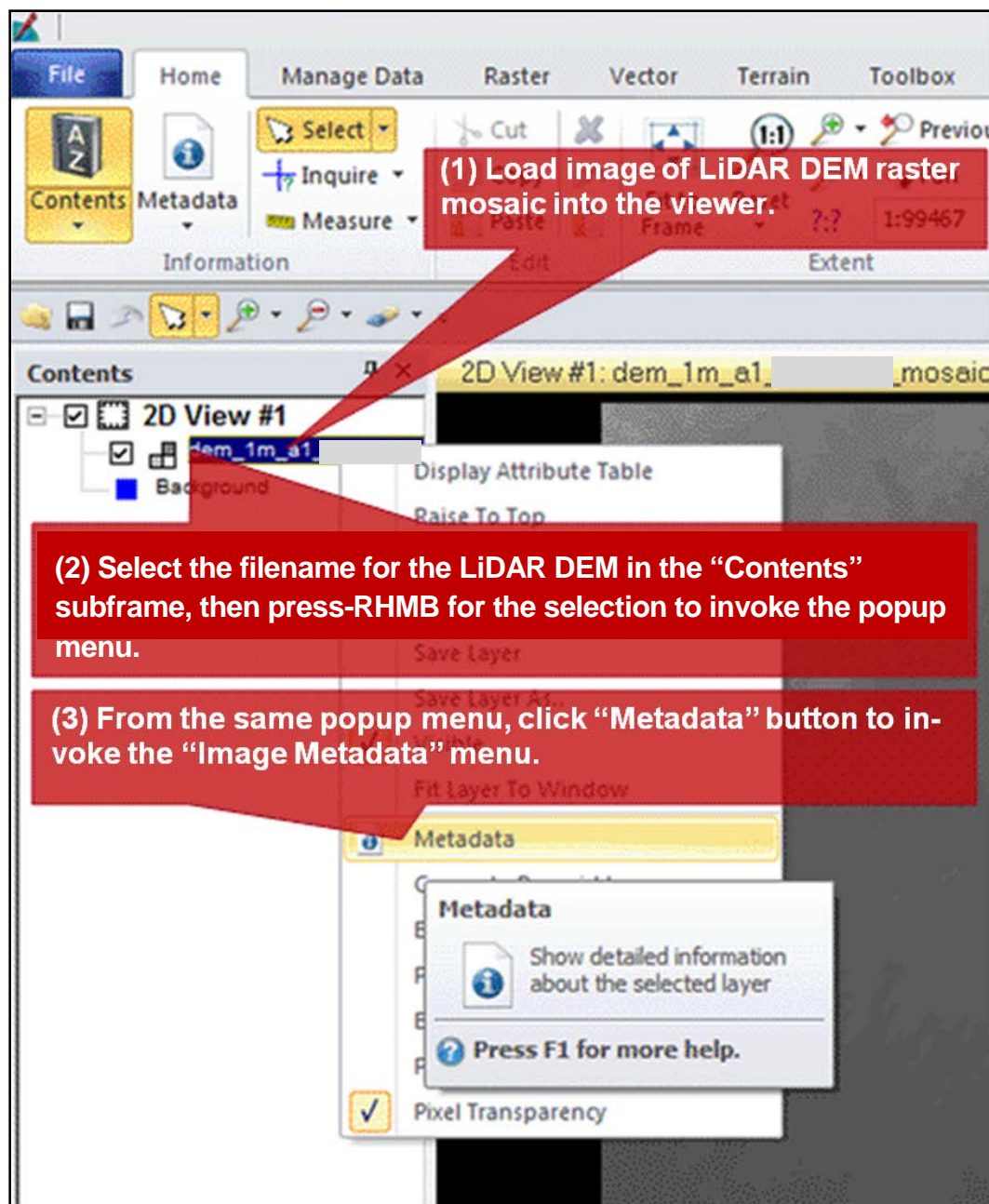


Figure 2-22. Terrain heights elevation metadata.

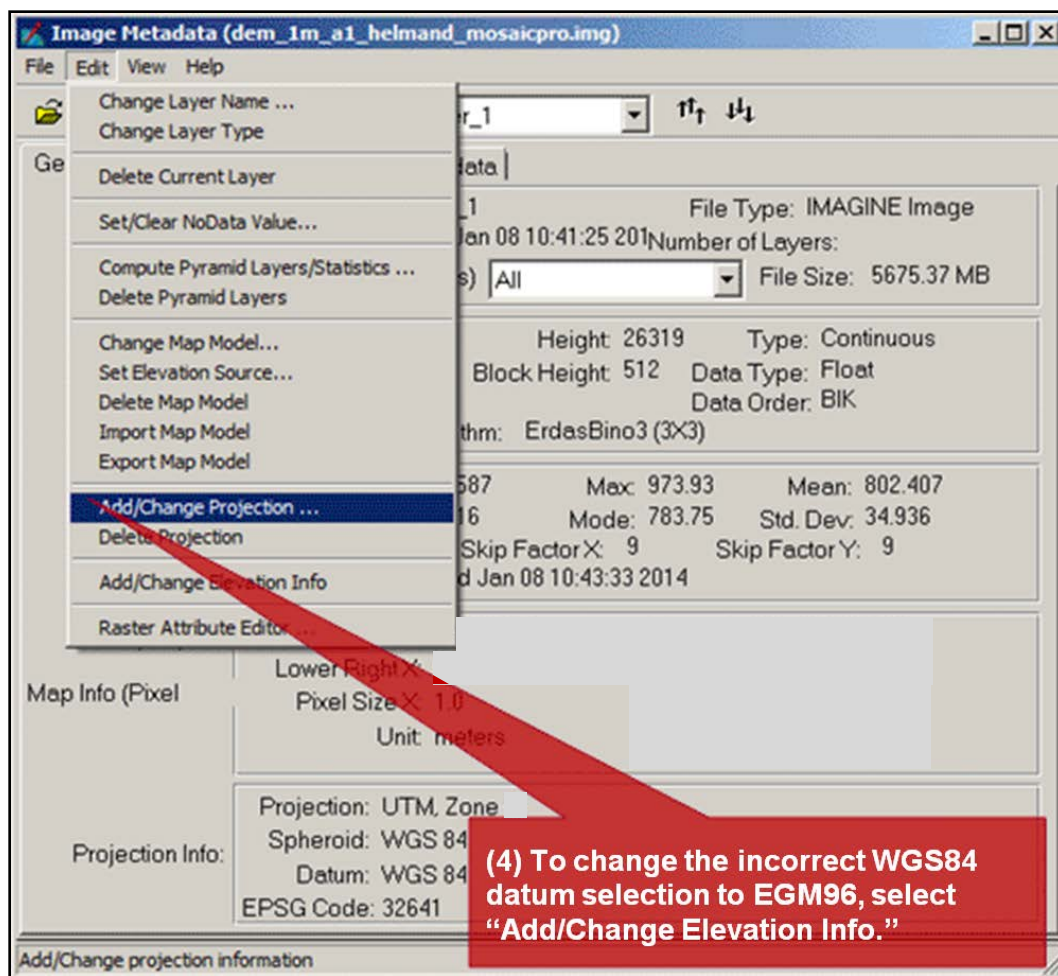
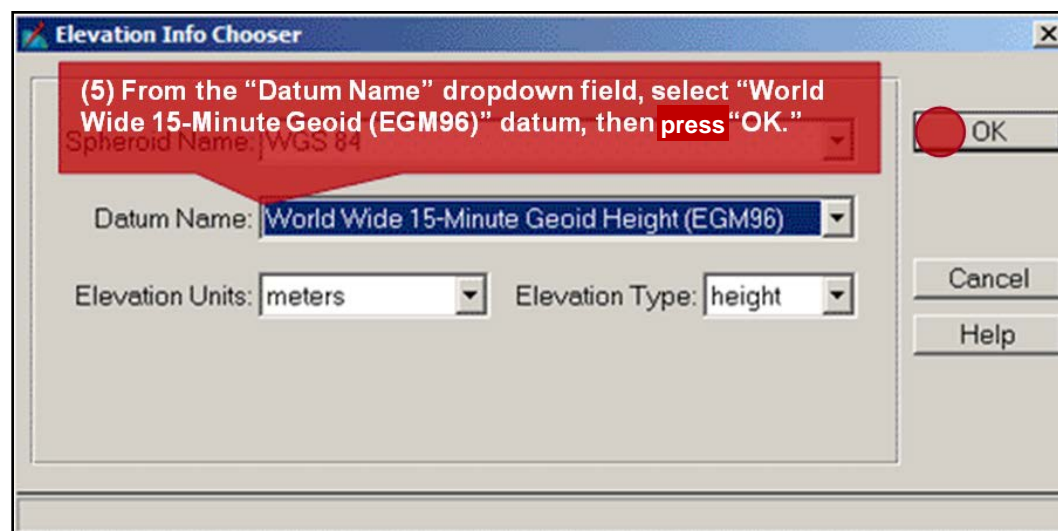


Figure 2-23. Choosing vertical datum for terrain elevations.



Figures 2-24 and 2-25 show how to acquire the “Image Metadata” for one of the overlapping NITF MSI frames that the orthoimage mosaic will include. The other overlapping but southeast WorldView-2 image frame has similar metadata.

1. Select the MSI frame name. (It will highlight in blue.)
2. Press-RHMB the selection to invoke the popup list.
3. Select “Metadata” from the popup list.
4. The “Projection Info” for the MSI frame should be “WGS84 Geographic (Lat/Lon).”

Figure 2-24. Review projection metadata for MSI.

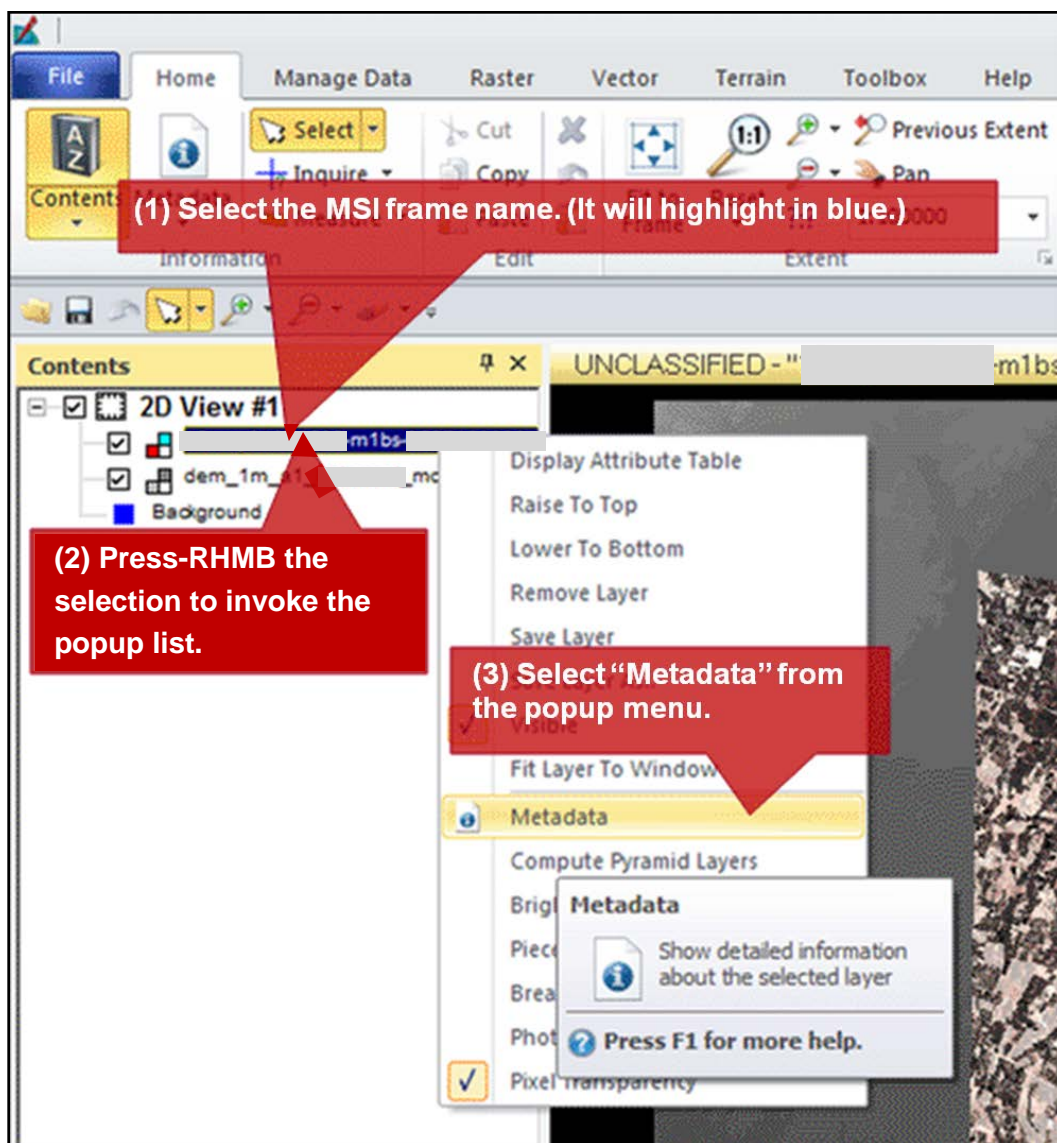
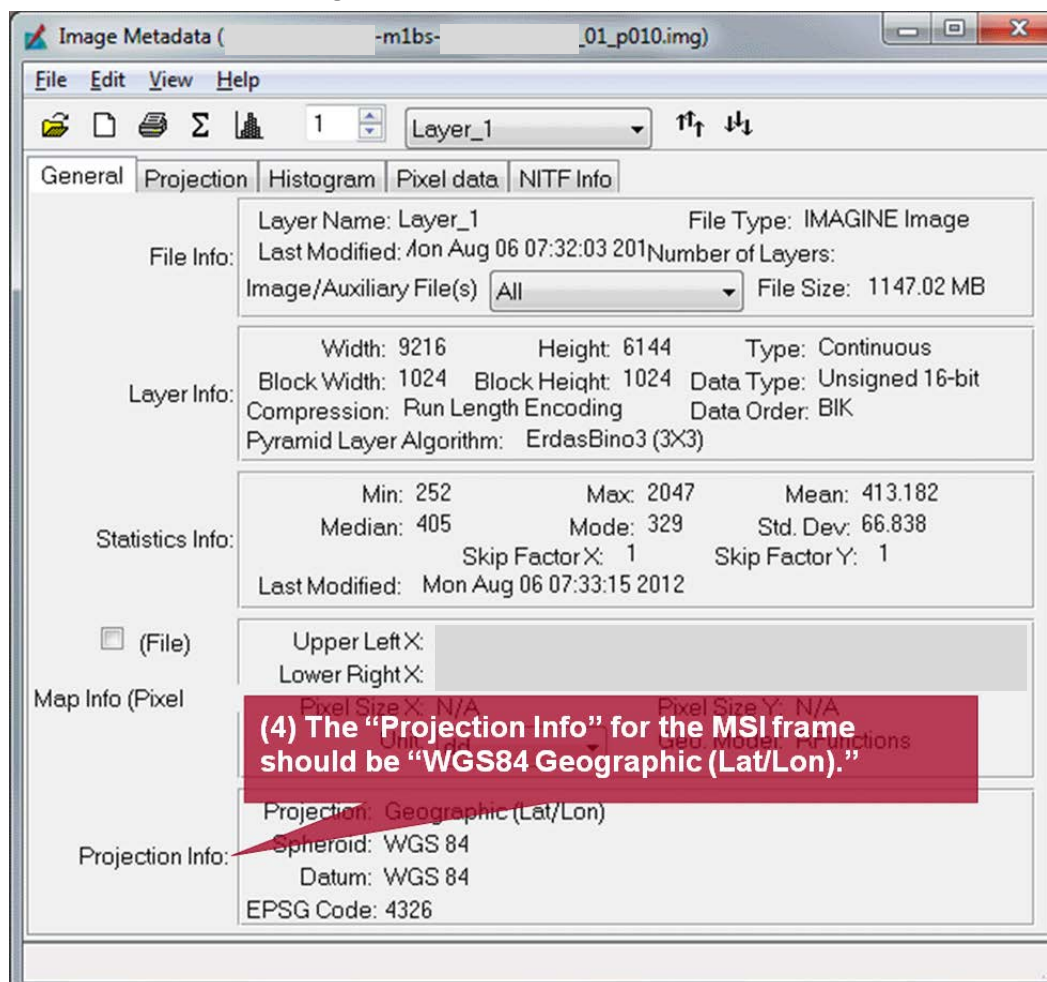


Figure 2-25. MSI projection and datum.



Figures 2-26 through 2-32 (Steps 1-8) show how to convert the EGM96 terrain heights into WGS84 elevations. The same UTM projection with the adjusted terrain heights will be converted to longitude and latitude in decimal degrees afterwards for use with the RPC of the MSI so that the WGS84 terrain heights will match both the datum and the projection expected by the MSI RPC sensor model.

1. Select the terrain height elevation mosaic filename.
2. In the “Help” tab, place the cursor in the “Search Commands” Field, then type “wgs.”
3. In the “Help” tab, go to the “results found” group, then press “Recalculate Elevation Values.”
4. Press the “Define Output Elevation Info” button.
5. In the “Elevation Info Chooser” menu, select “WGS84” from the “Datum Name” dropdown, then press “OK.”

6. In the “Recalculate Elevation for Images” menu, click the folder icon next to the Output File field.
7. In the “Output File” menu, Type in “File name” for the output converted elevations, then press “OK.”
8. In the “Recalculate Elevations for Images” menu, press “OK.”
9. In the popup “Process List” menu, when the State is “DONE – Click Dismiss to Remove,” then press “Close.”

Figure 2-26. Recalculate terrain heights elevation values.

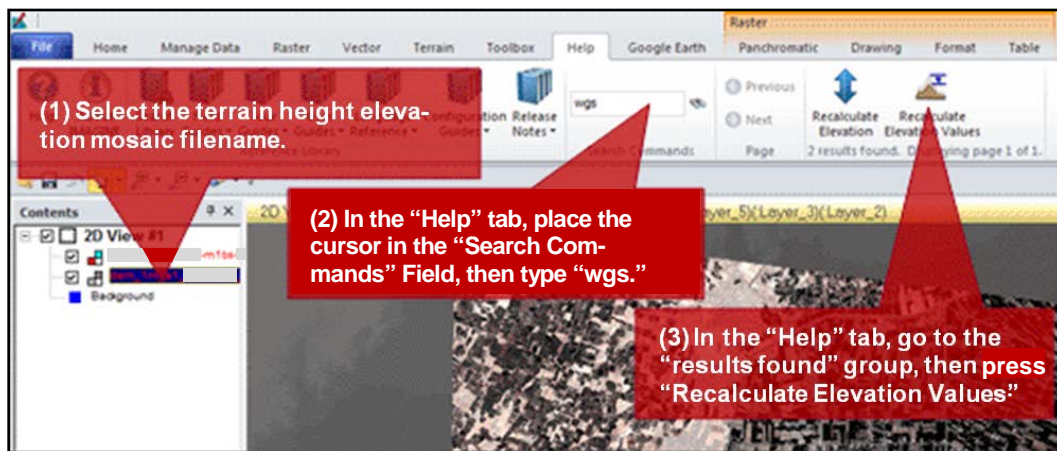


Figure 2-27. Define output elevation vertical datum.

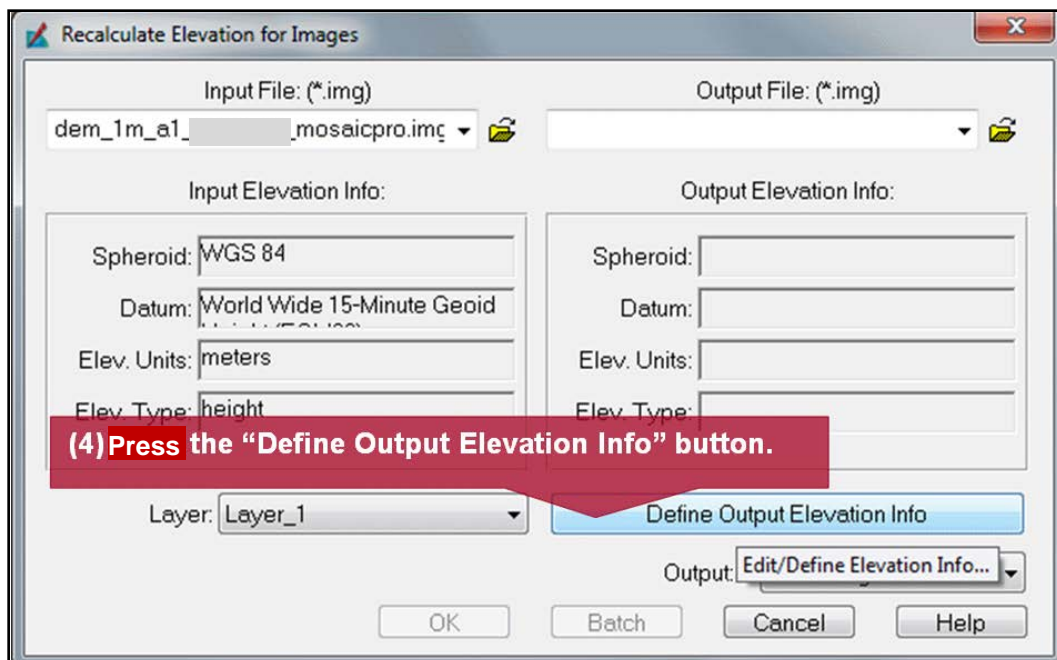


Figure 2-28. Project terrain heights from EGM96 to WGS84 vertical datum.

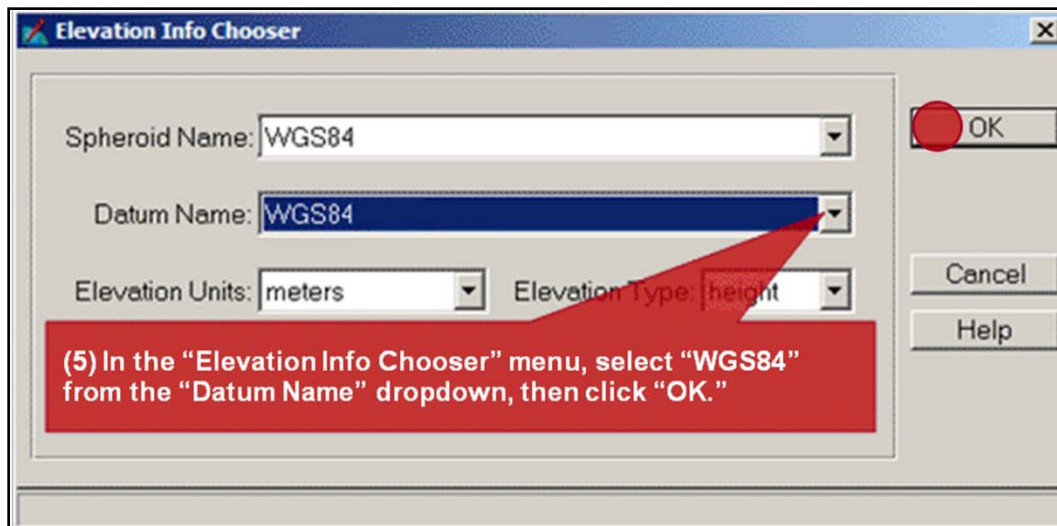


Figure 2-29. Convert WGS84 terrain heights from EGM96 to WGS84.

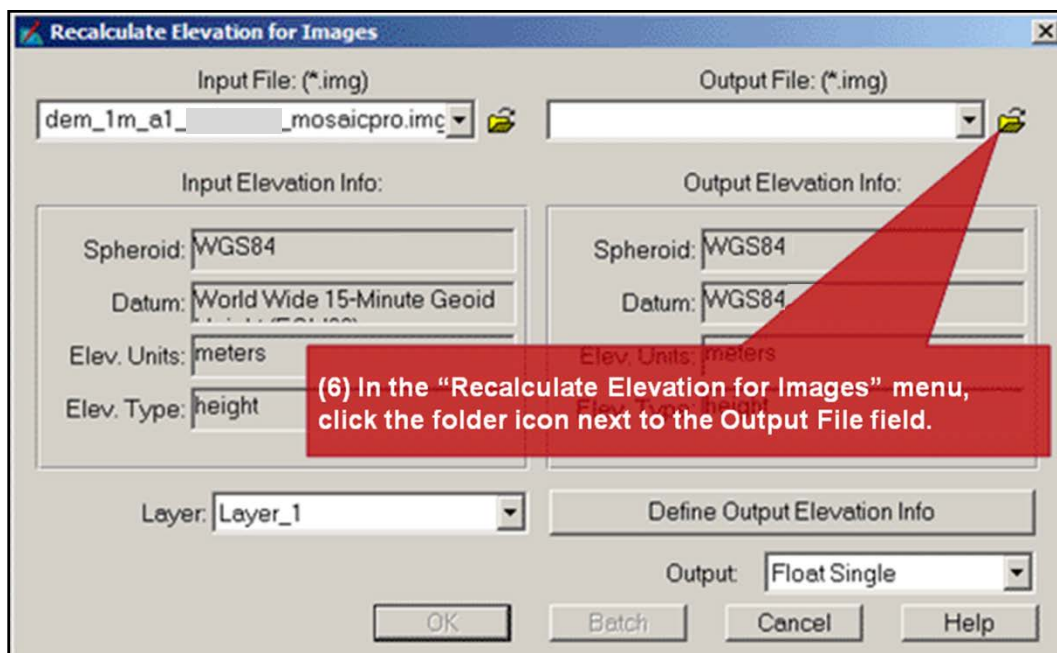


Figure 2-30. Filename output for WGS84 terrain heights from EGM96.

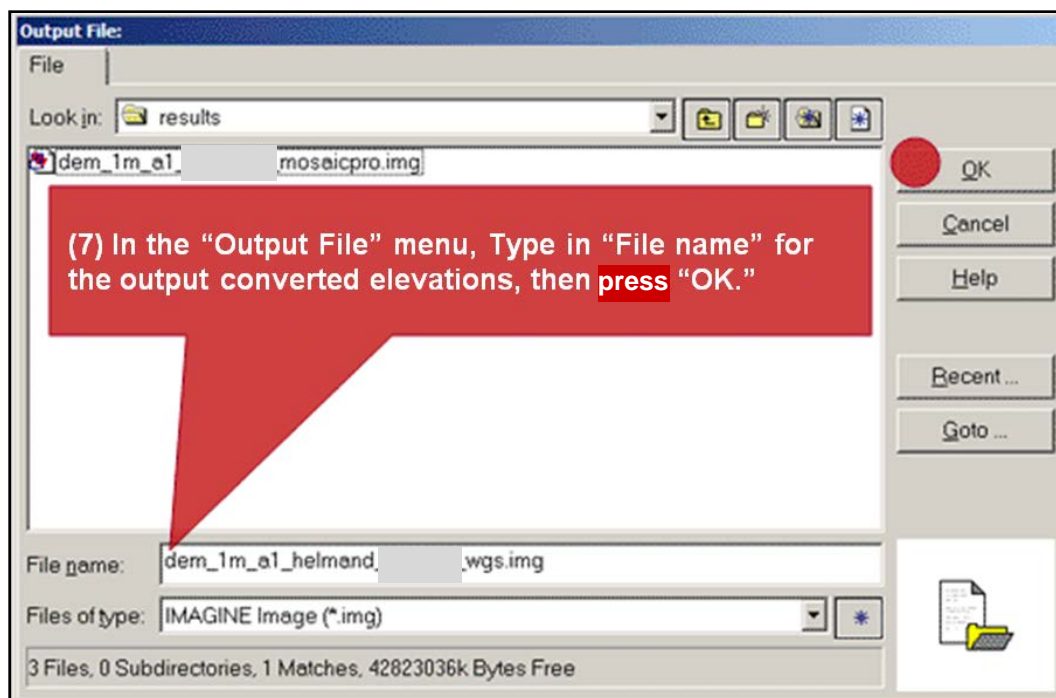


Figure 2-31. Convert terrain heights from EGM96 to WGS84.

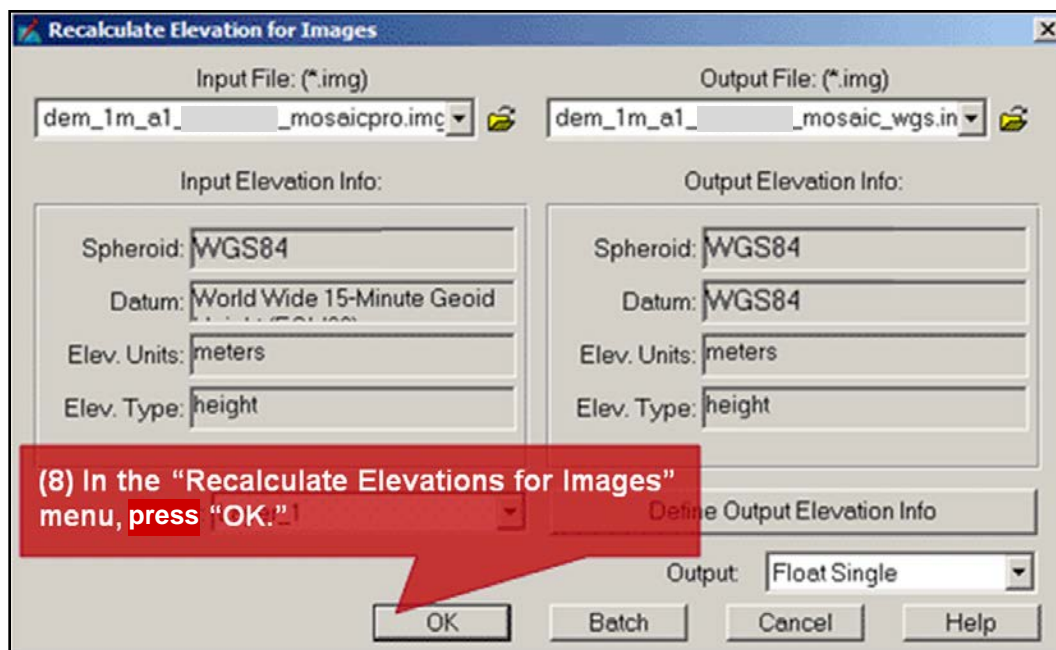


Figure 2-32. Close processing list to complete conversion.



2.7 Convert LIDAR DEM from UTM to geographic decimal degrees

Figures 2-33 through 2-35 and Steps 1-9 show how to convert from the UTM projection (with adjusted terrain heights) toward decimal degrees of geographic longitude and latitude. The Output Filename within the yellow box in Figure 2-34 is the input Elevation File for Step 5 in Figure 2-39.

1. In the “Help” tab, type “reproject” into the “Search Commands” field.
2. In the “Results Displayed” group, press the blue “Reproject” button.
3. Enter the “Input File” and “Output File” names into the “Reproject Images” menu. (The input and output filenames will be different.)
4. Select “Geographic” and “Lat/Lon WGS84” from “Categories” and “Projection” dropdown fields.
5. Check the “Ignore Zero In Stats” checkbox.
6. In the “Output Cell Sizes” group, press the “Nominal” button.
7. In the “Nominal Cell Sizes” menu, select 1x1 m, then click “OK.”
8. In the “Reproject Images” group, select the “Rigorous Transformation” radio button.
9. Press “OK” to start the process.
10. In the popup “Process List” menu, when the State is “DONE – Press Dismiss to Remove,” press “Close.”

Figure 2-33. Start projection of DEM raster from UTM to geographics.



Figure 2-34. Settings for reprojected images.

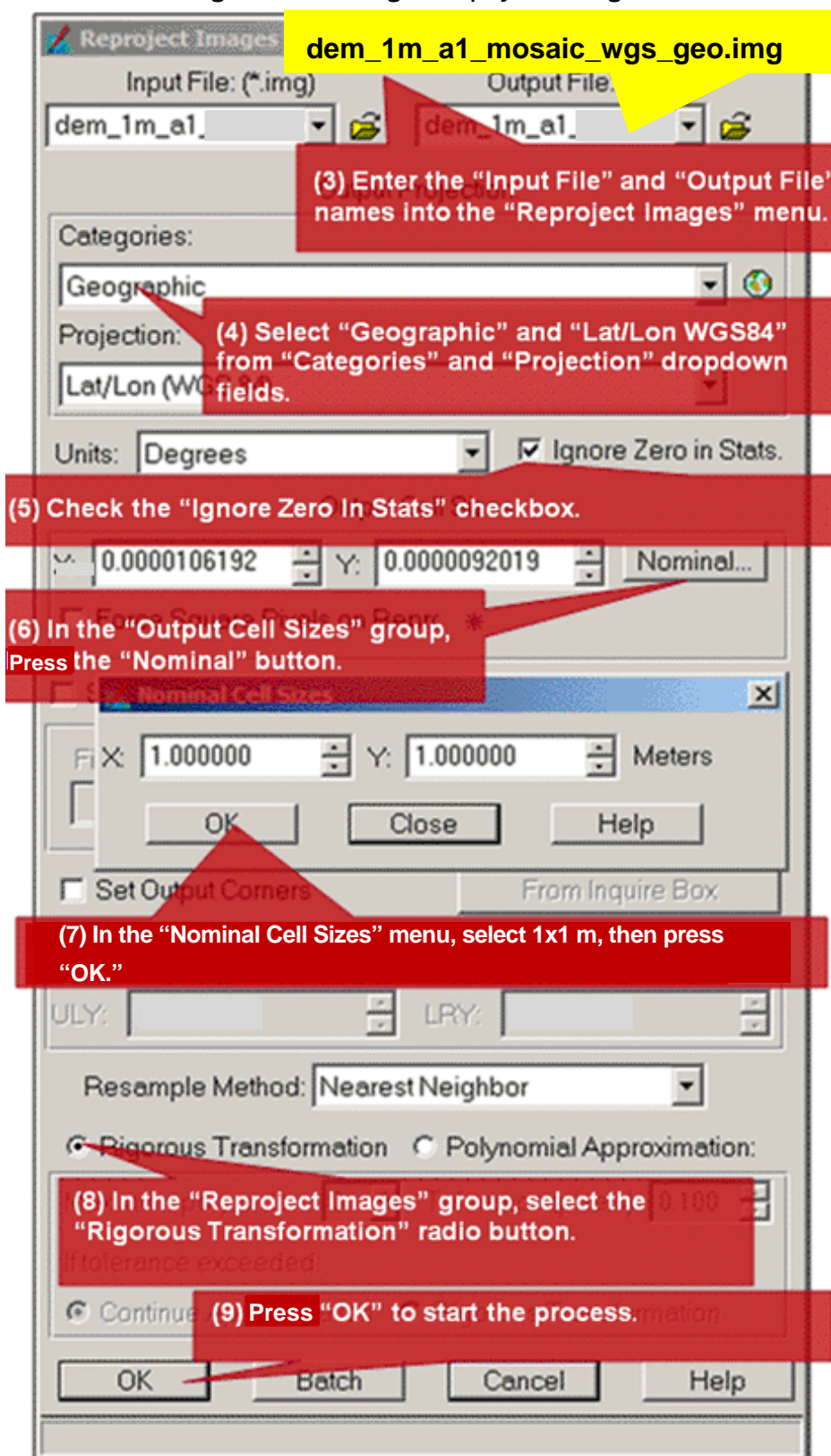
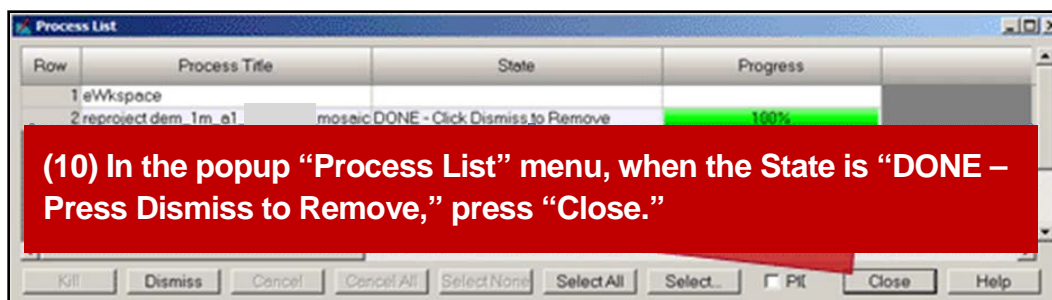


Figure 2-35. Close completed reprojection process.



2.8 Making orthoimages

Figures 2-36 through 2-39 (Steps 1-5) show how to make the orthoimage for each MSI frame of NITF with RPC. It is unnecessary to load a raw MSI into the viewer to make its orthoimage. The Elevation Filename entered within Step 5 of Figure 2-39 that is the same Output File name from Step 3 of the earlier Figure 2-34, where the filename is shown within the yellow box in Figure 2-34 because was truncated within its shorter field there. The “WorldView RPC Model...” menu will remain open after you press its “Apply” button, so you can close it by pressing the “Close” button afterwards but subsequent processing will be unaffected.

1. In the “Help” tab, type “ortho” in the “Search Commands” field. In the “results found” group, press the “Orthorectify without GCP.”
2. In the “Geo Correction Input File” menu, enter the “*.ntf” input filename, then press “OK.”
3. From the “Set Geometric Model” menu, select “WorldView RPC,” then click “OK.”
4. In the “WorldView RPC Model ...” menu, enter the “*.RPB” filename into the “RPC File” field.
5. For “Elevation Source,” select the “File” radio button, enter the filename into the “Elevation File” field, press “Apply,” then press “Close.”

Figure 2-36. Begin the orthoimage process.

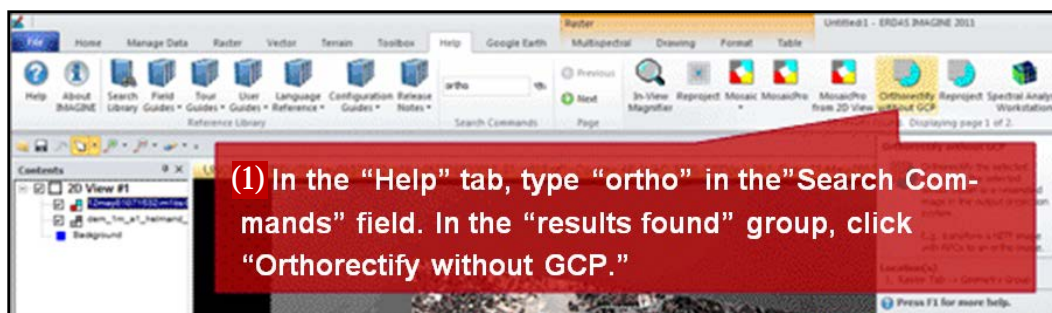


Figure 2-37. Pick NITF filename for making orthoimage.

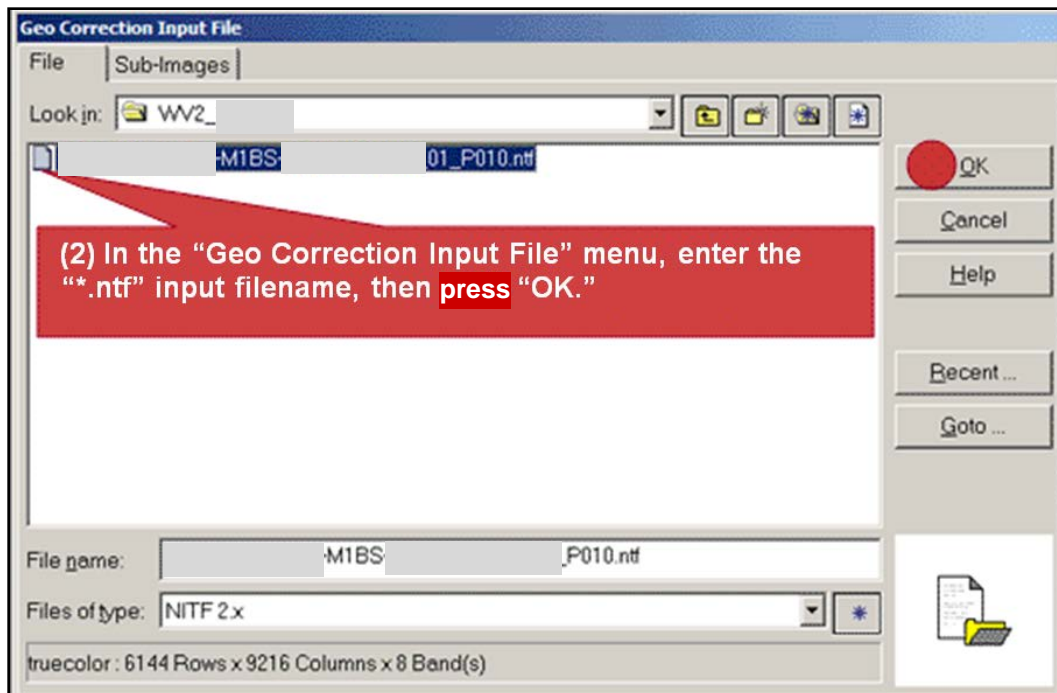


Figure 2-38. Show RPC model.

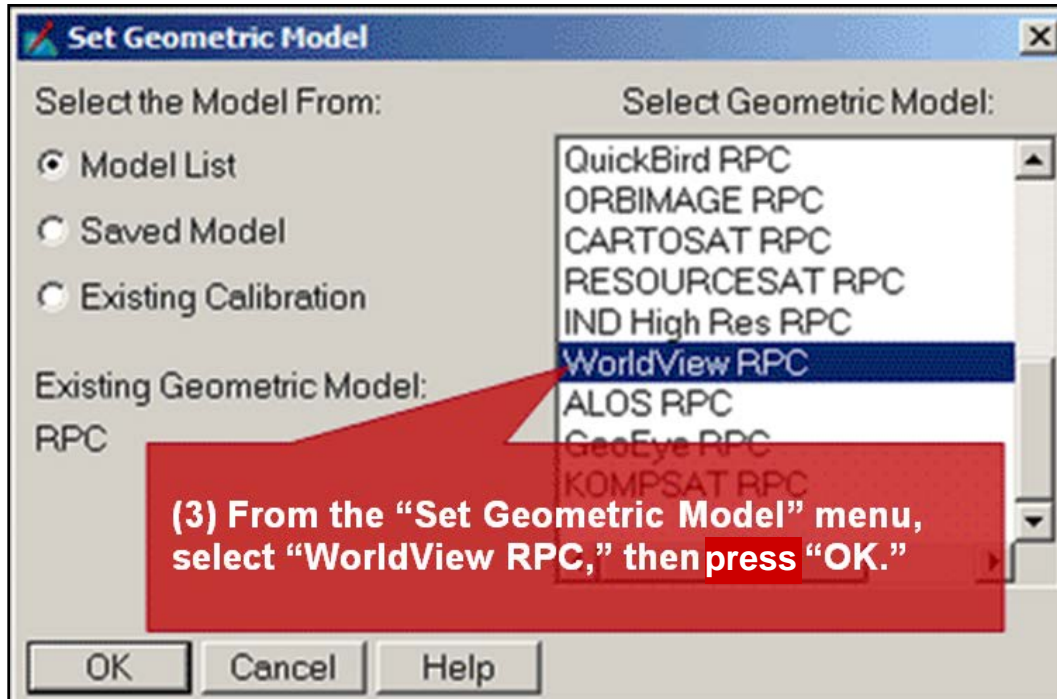
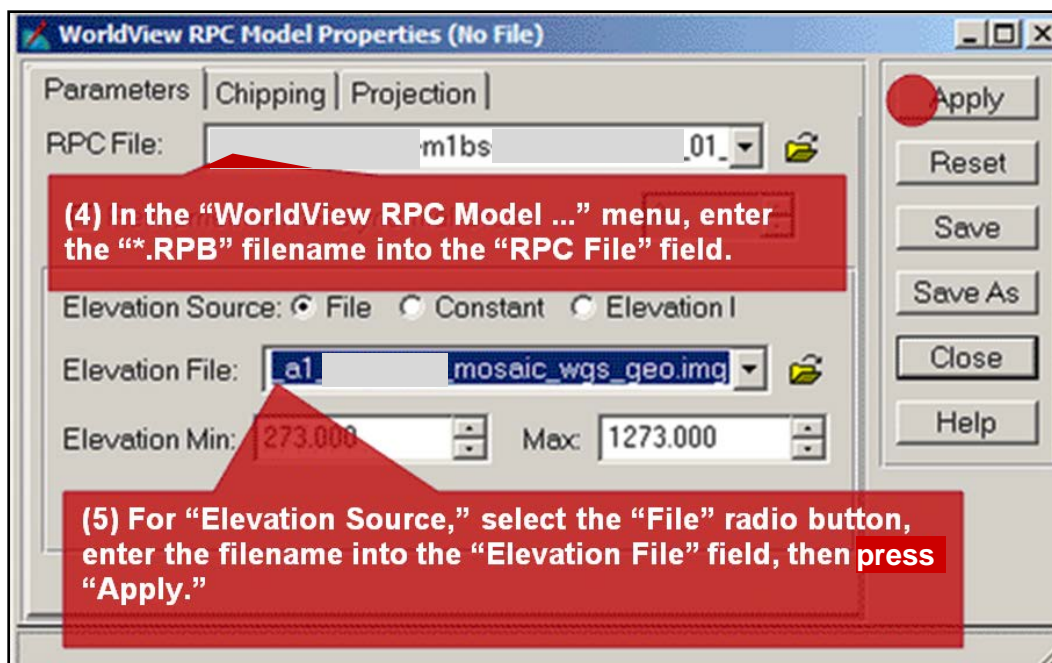


Figure 2-39. Show DEM raster.



After the “Resample” menu is applied then closed following Step 5, follow the steps shown in Figure 2-40 (Steps 6-12) to start making the orthoimage. Note that Steps 6-7 are not shown in Figure 2-40. These two optional steps allow you to change the default output GSD suggested by the software for each orthoimage. Skip Steps 6-7 to retain the output GSD suggested by the software. Appendixes B and D include more detail about choosing other output orthoimage GSD values. Use the same DEM raster mosaic filename from Step 5 in Figure 2-39 for Step 10 in Figure 2-40.

6. (Optional) Press the “Feet/Meter Units” button in the “Resample” menu, and check their values in the “Nominal Cell Sizes” popup.
7. (Optional) Put GSD values besides the ones shown into the “X” and “Y” fields in the “Nominal Cell Sizes” menu to match the Elevation File sizes. Press the “Apply” then “Close” buttons in the “Nominal Cell Sizes” popup.
8. Enter the “Output File” name into the “Resample” menu.
9. Check the “Snap pixel edges to” checkbox, then select the “raster image” radio button.
10. Enter the same filename in the “Elevation File:” field into the “File to snap to” field.
11. Check the “Ignore Zero in Stats” checkbox.
12. Click “OK” to start making the orthoimage.
13. In the popup “Process List” menu, when the State is “DONE – Click Dismiss to Remove,” press “Close.”

Figure 2-40. Start making the orthoimage.

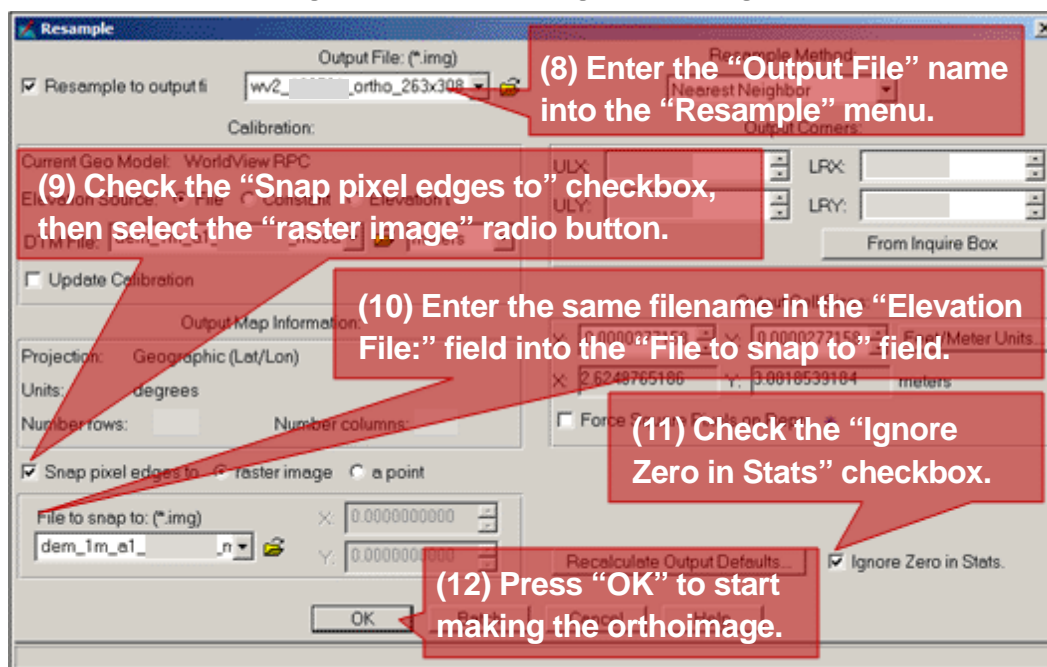
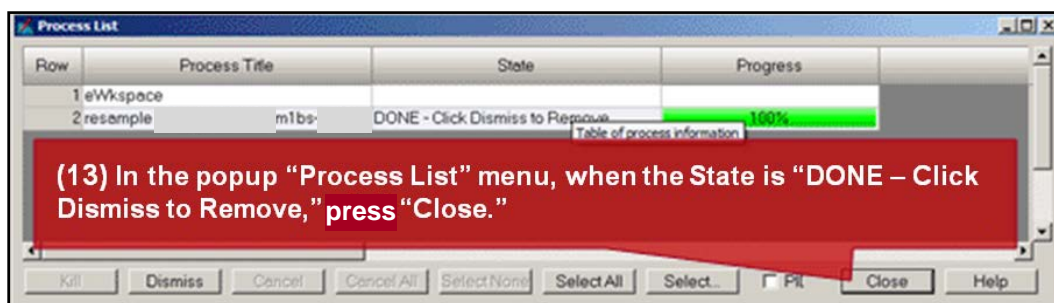
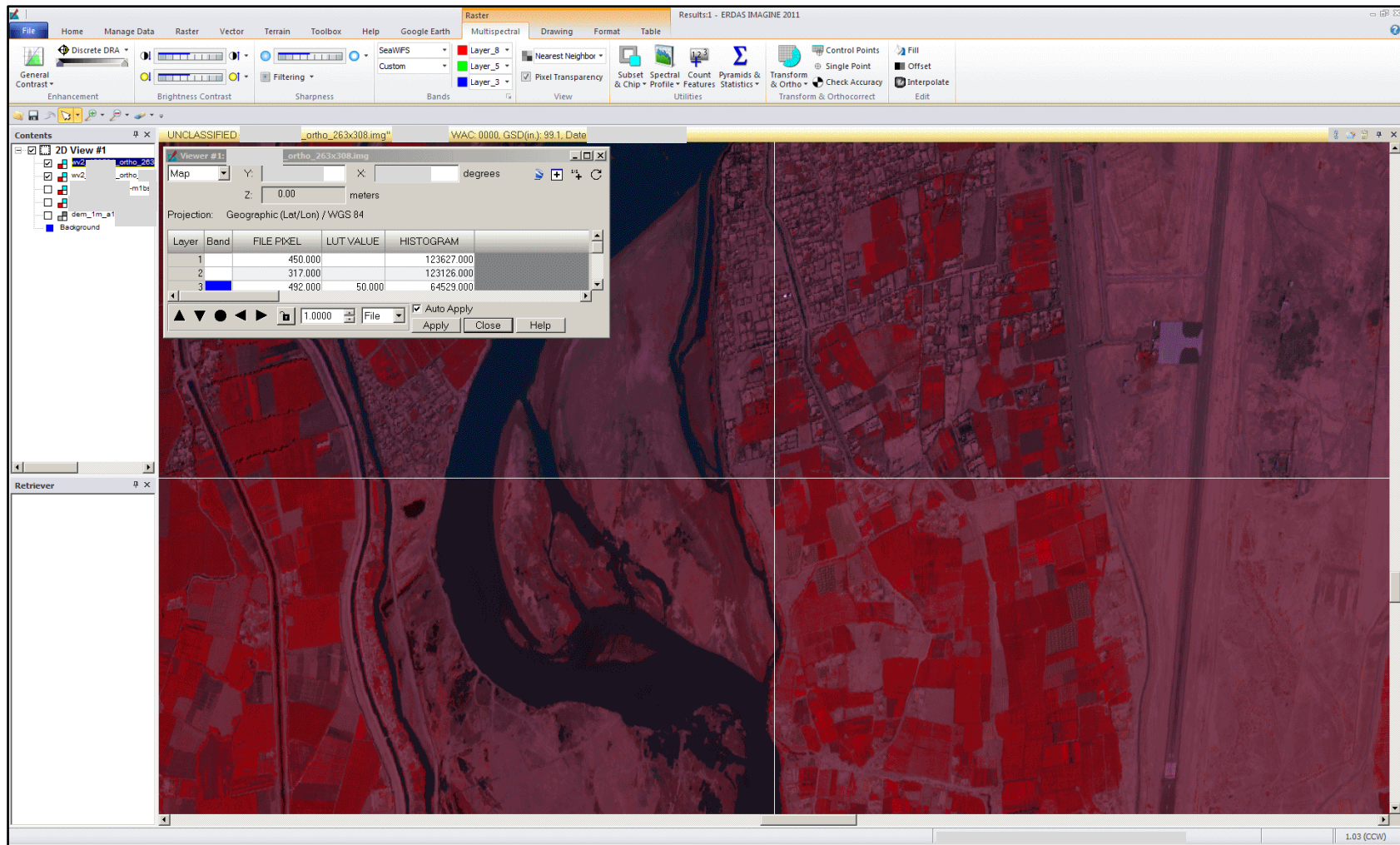


Figure 2-41. Close completed process for making orthoimage.



Figures 2-42 and 2-43 show how poorly the MSI frames match each other before making the orthoimages, and they show how the orthoimages match afterward from making them separately, while all MSI frames are in units of geographic longitude and latitude decimal degrees. It is worthwhile to compare the orthoimages where they overlap before converting them to the UTM projection that has the same horizontal and vertical units of meters. Note now how urban features besides buildings, say roads in urban areas, match each other better geometrically where they overlap. Use the "Swipe" tool to compare the MSI orthoimage with the DEM raster image underneath them in the viewer.

Figure 2-43. Overlapping MSI after making both orthoimages.



2.9 Create UTM orthoimage

Figures 2-44 and 2-45 show how convert the geographic longitude and latitude orthoimage into a UTM projection so that the MSI orthoimage pixels will align with the LiDAR terrain heights elevation grid. It is unnecessary to load the orthoimage into the viewer to convert it to UTM. The software automatically puts the “Reproject” button into the “results found” field of the “Help” tab from Step 1. Press the “Reproject” button (identified by its blue crescent shadow). In Step 2, the input filename is for the orthoimage in a geographic longitude and latitude projection; the output filename is for the orthoimage converted to the UTM projection. This allows horizontal distance measurements in meters on the orthoimage mosaic because of its new UTM projection.

1. On the “Help” tab, enter “reproject” in the “Search Commands” field, then press the “Reproject” button.
2. In the “Reproject Images” menu, enter both input and output filenames into their respective fields.
3. Select “UTM WGS84 North” from the “Categories” filenames for dropdown menu.
4. Select “UTM Zone 41 (Range 60E – 66E)” from the “Projection” field dropdown.
5. Select “Meters” from the “Units” field dropdown.
6. Check the “Ignore Zero in Stats” checkbox.
7. Select “Rigorous Transformation” choice.
8. Press the “OK” button to start the process.
9. Select the “Rigorous Transformation” radio button.
10. Press “OK” to start the process.
11. In the popup “Process List” menu, when the State is “DONE – Click Dismiss to Remove,” press “Close.”

Figure 2-44. Resample geographic MSI orthoimage to UTM projection.



Figure 2-45. Reproject images menu.

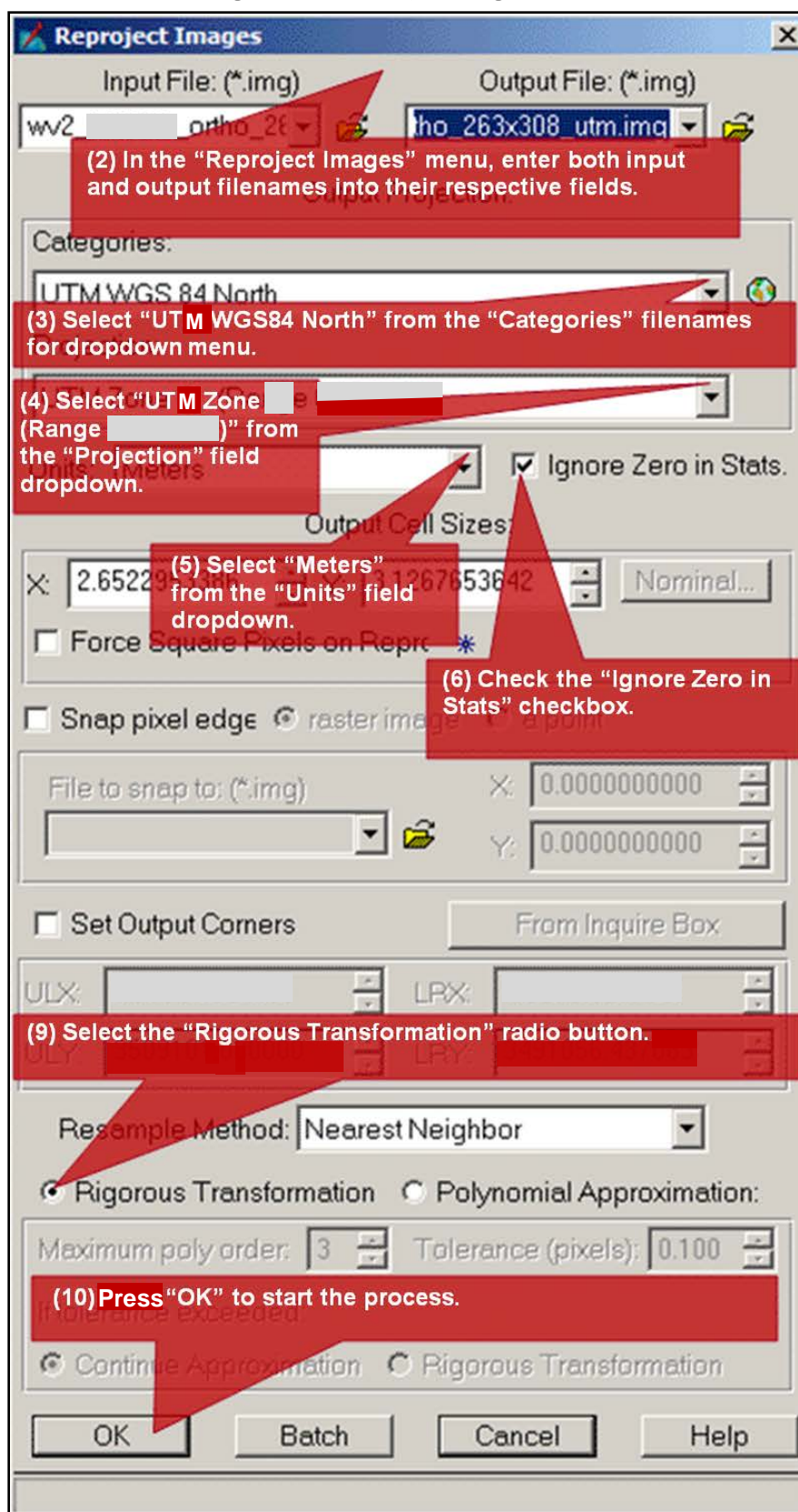


Figure 2-46. Processing list reproject progress.

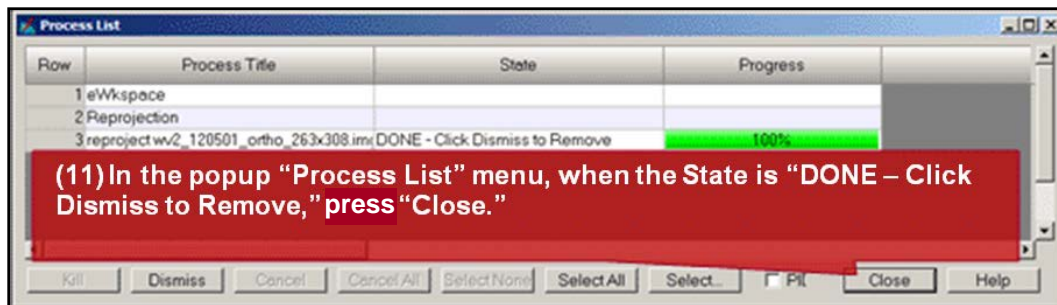
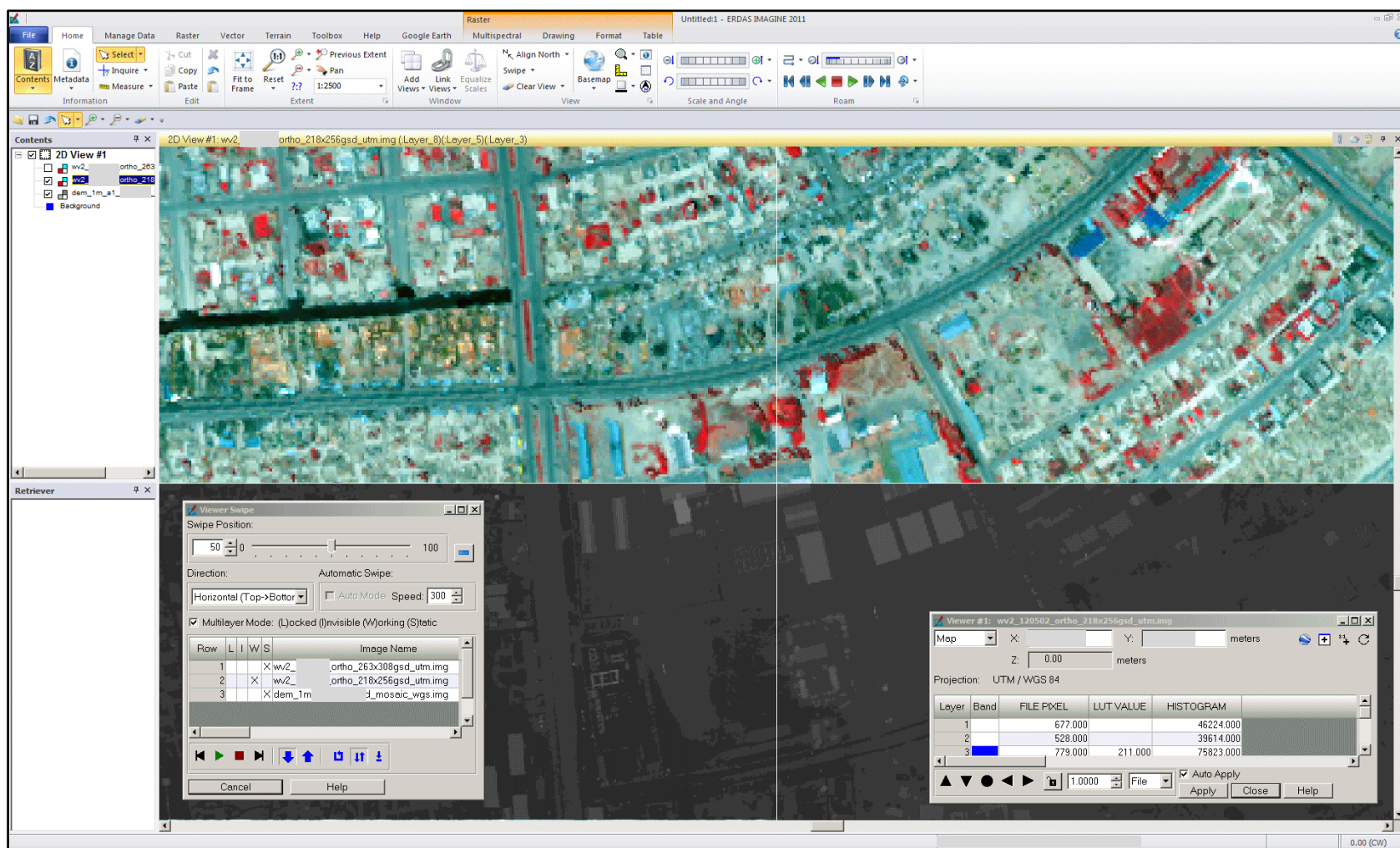


Figure 2-47 shows how well a completed false color orthoimage with its UTM projection aligns with the image of the LiDAR DEM raster. It is now possible to expand the area covered by MSI by adding all separately produced orthoimages to a mosaic of adjacent and overlapping orthoimages, where the mosaic has the same GSD throughout.

Figure 2-47. Orthoimage alignment with LiDAR terrain heights image.



3 Conclusions and Recommendations

3.1 Conclusions

This tutorial described procedures for making orthoimages from LiDAR DEM and from commercial satellite MSI in the NITF with RPF. Orthoimages rectify digital imagery to remove geometric distortions that are caused by the varying elevations of the exposed terrain features, and by the exterior and interior orientations of the sensor. When individual orthoimages are combined, the resulting mosaic covers a wider area for image-maps and it contains less visible seams where the orthoimages overlap, making the user more comfortable when reviewing image-map products. The processes in this tutorial will enhance the production of orthoimage mosaics used by the Army Geospatial Center and ERDC-GRL as image-map products that aid tactical decisions and improve situational awareness.

The procedures described for making orthoimages also should work when combining other DEM and MSI data with different resolutions. Other DEM that lack the spatial resolution of LiDAR may include Digital Terrain Elevation Data (DTED) for example, global Shuttle Radar Topography Mission (SRTM), Interferometric Synthetic Aperture Radar (IFSAR), or the terrain elevations from stereo correlation of the original MSI or its panchromatic band that has one-quarter of the GSD for the MSI bands. The LiDAR is preferred, however, because of its better spatial resolution to improve the registration of DEM and MSI data (and to avoid the stereo correlation for terrain elevations with the overlapping panchromatic bands) for example in urban areas with many elevation discontinuities from manmade structures.

3.2 Recommendations

To better process higher resolution images, it is recommended that future research reassess current practices of feature extraction from the LiDAR DEM raster and commercial satellite MSI data that are combined in the process of making orthoimages, where feature extraction for models of surface material in urban areas will improve from the better spatial resolution of LiDAR and the orthoimages produced from it.

The process outlined in this tutorial described two overlapping, but separately produced orthoimages, but it ignored tonal imbalance and output GSD discrepancies between orthoimages in a mosaic. It is recommended that future research investigate methods to remove such geometric discrepancies, including tonal imbalance between both orthoimages.

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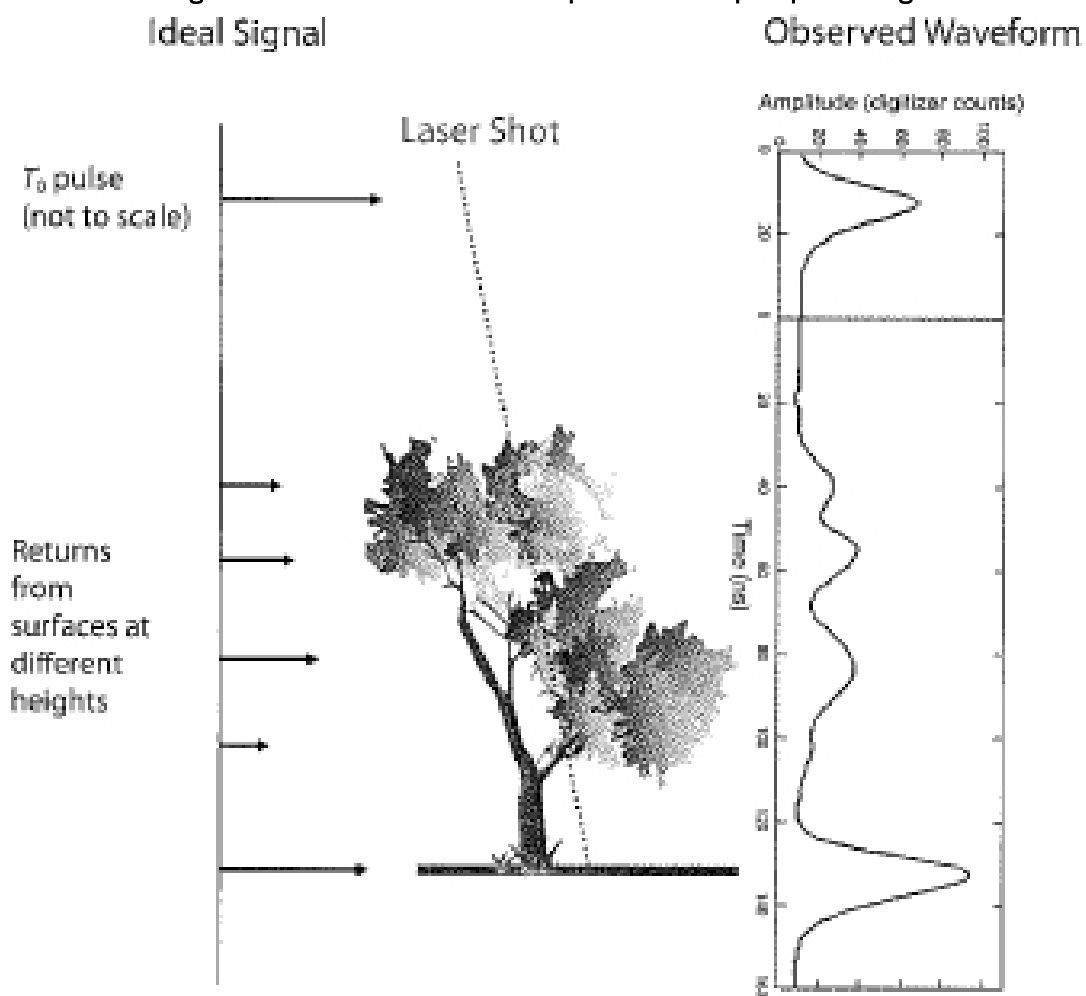
Acronyms and Abbreviations

<u>Term</u>	<u>Definition</u>
AGC	U.S. Army Geospatial Center
AGC-GRL	U.S. Army Geospatial Center – Geospatial Research Laboratory
ASPRS	American Society for Photogrammetry and Remote Sensing
CCD	Charge-Coupled Device
CEERD	U.S. Army Corps of Engineers, Engineer Research and Development Center
DEM	Digital Elevation Model
DTED	Digital Terrain Elevation Data
EGM96	Earth Gravity Model 1996
EM	Engineer Manual
ERDC	Engineer Research and Development Center
ERDC-GRL	Engineer Research and Development Center-Geospatial Research Laboratory
FM	Field Manual
GCP	Ground Control Point
GSD	Ground Sample Distance
GSFC	Goddard Space Flight Center
HQDA	Headquarters, Department of the Army
HQUSACE	Headquarters, U.S. Army Corps of Engineers
IEEE	Institute of Electrical and Electronics Engineers
IFSAR	Interferometric Synthetic Aperture Radar
LiDAR	Light Detection and Ranging
LLC	Limited Liability Company
MSI	Multi-Spectral Imagery
NASA	National Aeronautics and Space Administration
NIMA	National Imagery and Mapping Agency
NITF	National Imagery Transmission Format
RPC	Rational Polynomial Coefficients
SF	Standard Form
SRTM	Shuttle Radar Topography Mission
TIFF	Tagged Image File Format
TR	Technical Report
U.S.	United States
USACE	U.S. Army Corps of Engineers
UTM	Universal Transverse Mercator
WGS84	World Geodetic System 1984

Appendix A: LiDAR DEM Raster

Figure A-1 shows the processing of a single LiDAR laser shot (commonly called a “pulse”) to find points along the recorded waveform of its reflected return (Pack, et al., 2012). This process usually finds peaks along the waveform that show a strong returned laser signal reflected from a relatively solid terrain surface or subsurface for the entire time along its range of the laser shot. Each waveform measures and records the continuous strength of the reflected return throughout the time interval when each laser is shot from the sensor and then reflected back toward it.

Figure A-1. Motivation for initial step of waveform post-processing.



This process forms a three-dimensional cloud of points, each with a returned value for the overall returned strength of the signal. The X, Y, and Z value for each point in the cloud is determined relative to the known exterior and interior orientation of LiDAR sensor, at given times, along the entire waveform. This point cloud is sampled to produce a uniform raster for the DEM that is used when making orthoimages. The first peak along each waveform becomes an elevation value for the reflective surface of the terrain skin. These points are converted to a uniform grid of X, Y, Z-elevation values that form the DEM raster. This DEM raster of terrain heights from the first return is used when making an orthoimage.

Appendix B: Orthoimage Spatial Resolution

This appendix describes options for producing orthoimages and the impacts on the orthoimage if one uses output spatial resolutions other than the nominal GSD of the raw MSI suggested by the software. For example, one might wish to specify a consistent output spatial resolution between each separately produced orthoimages that are combined together in a mosaic.

The nominal dimensions for the raw MSI are expressed as the GSD for the width and length of each MSI pixel footprint on the terrain. The spatial resolution for the DEM raster grid-cell is expressed as the GSD in meters for the UTM projection. The DEM also has a spatial resolution different from that of the raw MSI. These different spatial resolutions are important because an orthoimage is constructed by finding the unknown nearest pixel in the raw MSI given the known X, Y, and the estimated Z value that is the terrain height found for the DEM raster cell.

Producing an orthoimage with the same output spatial resolution as the DEM is a practical way to register both datasets together for two reasons:

1. It will be unnecessary to estimate terrain height values by interpolating from the DEM when producing the orthoimage, which allows the use of the terrain heights directly from the DEM when producing the orthoimage with the ground-to-image sensor model.
2. The produced orthoimage will have a single terrain height value associated with each orthoimage grid-cell along with a vector of brightness values from each layer of the MSI, so that additional channels derived from the DEM raster can serve as extra layers during MSI feature extraction.

The orthoimage also will contain rectangular or square pixels with a shape different from that of raw MSI pixel footprints on the ground, which will more nearly approximate the shape of a parallelogram. The array of MSI pixels also is oriented differently than the orthoimage pixels. An orthoimage has pixels oriented in the x-east and y-north directions, but the MSI pixel footprints are shaped by the orbital mechanics of the satellite platform and by the perspective of a push-broom scanner for WorldView-2 MSI. All of these concerns complicate conversions between the raw MSI and the orthoimage spaces. These differences between the shape and orientation of raw MSI pixel footprints on the terrain, relative

to the output orthoimage GSD, mean that the raw MSI requires resampling regardless of how close its nominal pixel footprint size is to output GSD for the produced orthoimage.

One must determine the output spatial resolution of the produced orthoimage to resolve issues involving the shape and size differences between the pixel footprints for separate frames of raw MSI, and for the different DEM raster shape/size. Although choosing a single output spatial resolution can make it difficult to retain the approximate nominal spatial resolution for each raw MSI frame, each separately produced orthoimage in a mosaic should have the same spatial resolution to prevent resampling when the orthoimages are combined into a mosaic.

However, the metadata for the MSI might include ranges of nominal GSD for the terrain footprint of its pixels. This information helps the software or user to decide the overall output spatial resolution for each separately produced orthoimage. Choices regarding the anticipated output spatial resolution of orthoimages must be made within the datum and projection of the final product required by the customer. This appendix provides guidance on choosing a common GSD for all orthoimages that are to be combined into a single mosaic.

Table B-1 lists the actual dimensions of pixel footprints on the ground for each overlapping MSI frame and of the LiDAR DEM raster for the material used in this tutorial. Values listed in Table B-1 were from the metadata for the MSI and the DEM. Note that the nominal GSD for the raw MSI is a range of values that reflect the fact that the MSI pixel GSD dimensions vary throughout its entire frame regardless of the terrain flatness. This complicates the decision that the software (or user) must make to determine the best single output resolution for each orthoimage in the mosaic.

Table B-1. DEM and MSI pixel dimensions.

	GSD meters (X-East)	GSD meters (Y-North)	GSD meters (Along Track Column)	GSD meters (Across Track Row)	GSD meters (Area-Square- Root) ^c
LiDAR DEM	1.0	1.0	NA	NA	1.000
MSI(1)^{def}	NA	NA	2.735 - 2.749	2.282 - 2.292	2.518
MSI(2)^{def}	NA	NA	2.305 - 2.314	2.151 - 2.162	2.242
Ortho(1)^{ab}	2.625611952	3.083660465	NA	NA	NA
Ortho(2)^{ab}	2.177177166	2.555811617	NA	NA	NA
Notes: a) The GSD meters in the X & Y directions for Orthos are offered default values by the ERDAS Imagine 2011. b) These are square pixels with angular units of decimal degrees, but they are rectangular pixel footprints with meter units. c) Square-root of the product for the average GSD along & across the satellite track gives a square pixel in meters. d) This is the footprint of square MSI pixels that are projected onto the terrain surface depicted by the DEM. e) The MSI pixel footprint has a parallelogram shape reflecting the exterior orientation of the sensor. f) The average MSI pixel footprint dimension on the terrain surface is the middle of the shown GSD range.					

Table B-1 lists a range of values for the nominal GSD for each pixel footprint. The size of each pixel footprint will differ even if the entire image is exposed instantaneously. The scale of each pixel is the distance from the focal point to the point on the focal plane divided by the range from the focal point to the spot in the DEM space; this affects the size of each pixel footprint that depends on elevation values that change across the entire image.

The shape of each MSI pixel footprint projected onto the terrain is nearly a parallelogram because its shape is affected by the exterior orientations of the sensor. These orientations are something other than 90-degree angles between the “along” and “across” scan directions of the sensor carried by the satellite platform. Consequently, the mathematics and projective geometry of photogrammetry, plus the terrain heights, affect the size and shape for each MSI pixel footprint differently. This accounts for the range of GSD and the lack of a single spatial resolution throughout the MSI frames (Forstner & Wrobel, 2013; Mugnier, et al., 2013).

It is unclear how the image processing software sets the output GSD when making the orthoimage given the range of nominal resolution for the MSI, in that it still needs to estimate Z values of terrain heights for other spots besides those of the current DEM raster. Although this tutorial ignores concerns about best methods to resample DEM rasters while making orthoimages, the default value for the resolution of the output orthoimage can, if desired, be changed to the resolution of the DEM, or to another common GSD for all of the separately produced orthoimages. This Appendix describes the resulting difference in one of the output orthoimages in which values chosen automatically by the software are:

- DEM GSD=1.0 m compared to a nominal MSI pixel footprint
- GSD=3.05 m in the x-east direction
- GSD>equals 2.61 m in the y-north direction.

Note that the nominal average GSD of the pixel footprints was 2.514 m for one MSI frame, and 2.242 m for the other MSI frame, because the MSI metadata provides this as a range of GSD values.

Figure B-1 shows a split view of the pixel footprint shape for the raw MSI and the orthoimage produced from it. Note that, on the left side of the viewer, the raw MSI pixel footprints are parallelograms. On the right side of the viewer, the orthoimage pixels are rectangles oriented perpendicular in the x-east and y-north directions. However, the raw MSI pixel footprints are parallelograms oriented with respect to the along-track of the satellite path, and to the across-track scan direction of the satellite, where the orientation of the MSI raster is affected by satellite orbital mechanics.

Moreover, the NITF metadata implies that these along-flight and along-scan directions are slightly other than perpendicular to each other. These parallelograms are square pixels in the sensor array that are reshaped by the exterior orientation of the sensor when they are projected to form their footprint on the terrain. The split view also shows the offsets of image-objects between the raw MSI and its orthoimage that are produced with a GSD suggested by the default values of the software. Tonal imbalance remains between the split views, but this makes it easier to distinguish between each image shown in the viewer.

Figure B-1. MSI and orthoimage equivalent spatial resolutions.

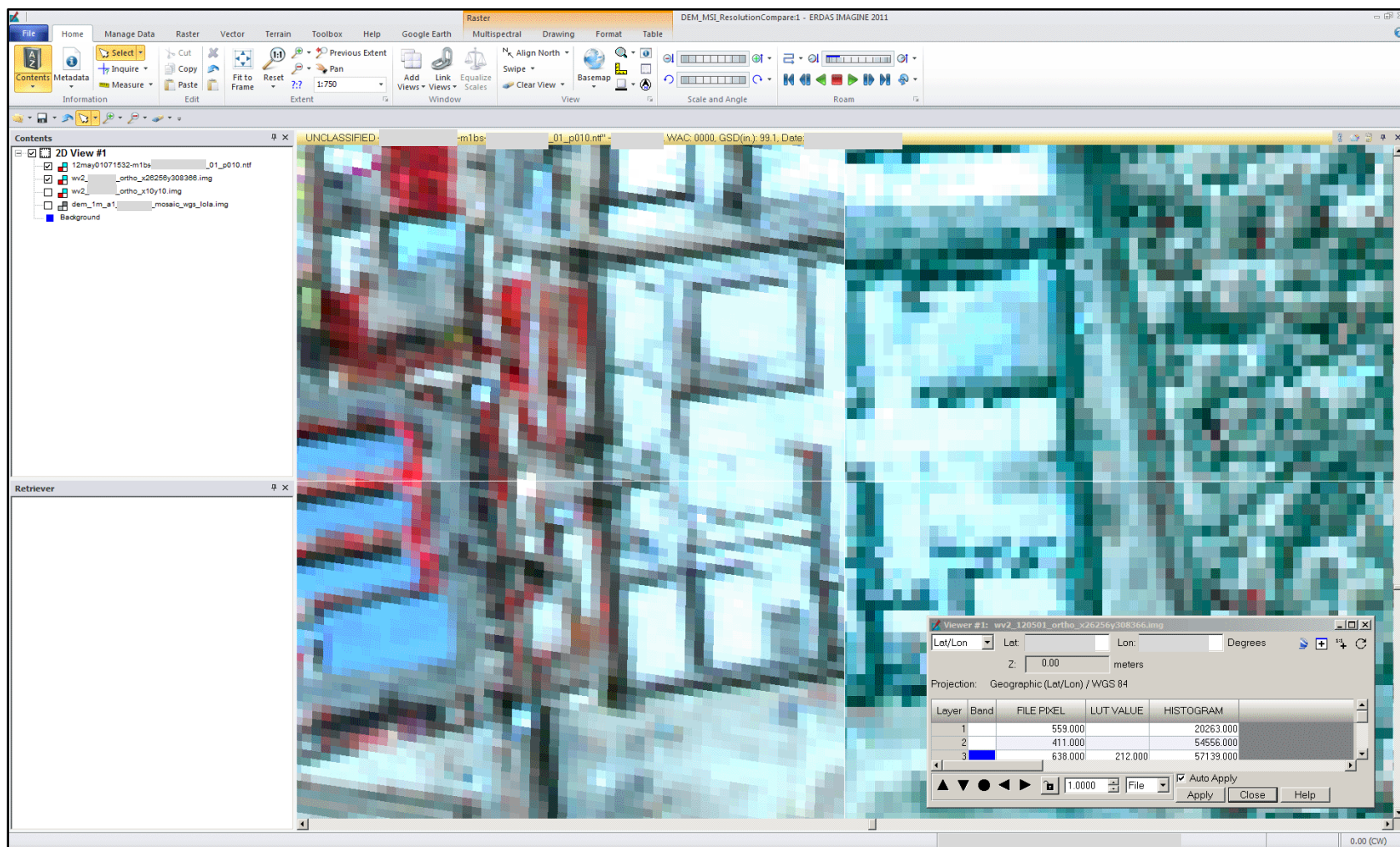


Figure B-2 shows the size of pixel footprints from the metadata for the produced orthoimage on the right side of Figure B-1, where the software automatically determines the suggested default output values that reflect the GSD spatial resolution, which is a square pixel footprint with units of decimal degrees.

Figure B-2. Default orthoimage pixel GSD In decimal degrees.

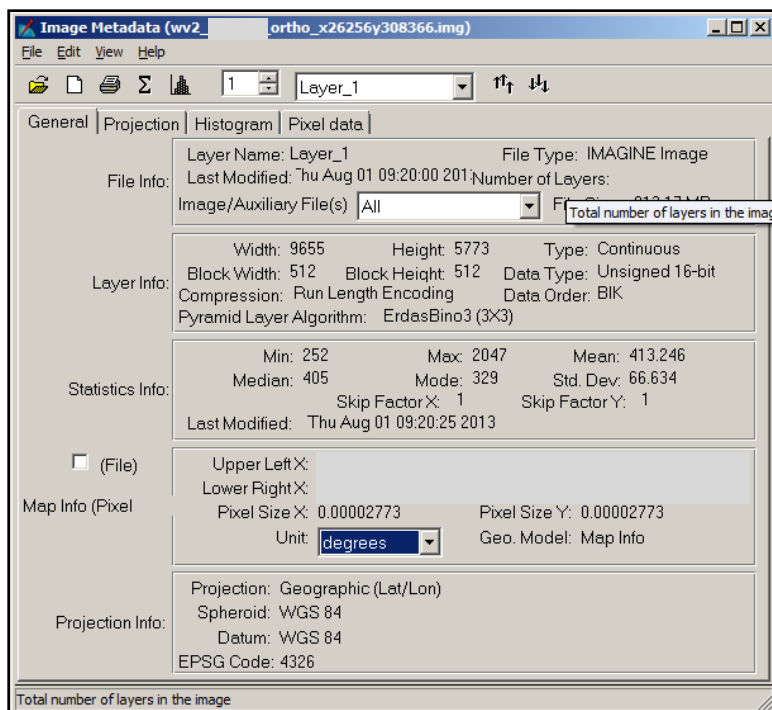
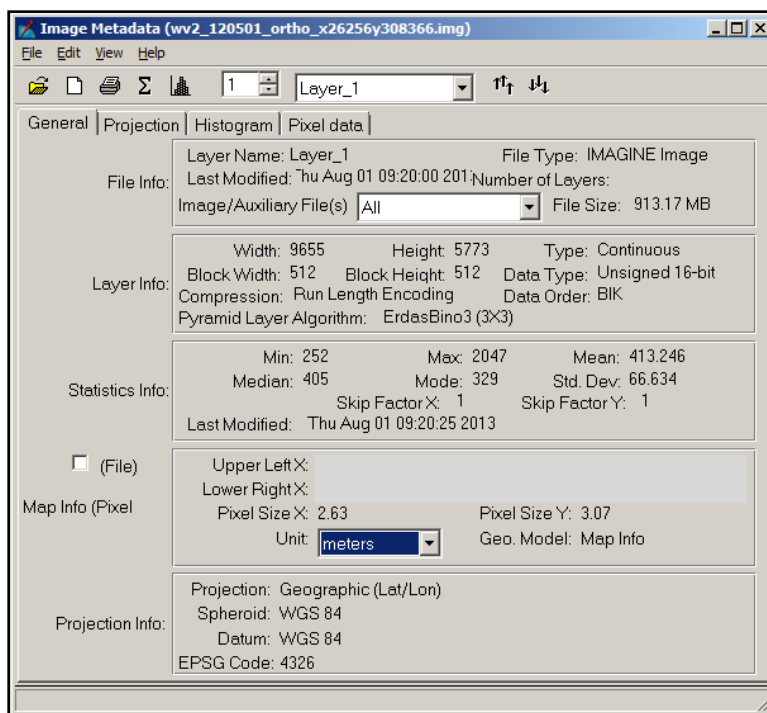


Figure B-3 shows the size of the orthoimage pixels in meters. This size reflects the nominal GSD from the raw MSI suggested by the software, which is a rectangular (instead of square) pixel width and length by meters in two perpendicular directions of east and north. The different shapes and orientations between the lattices of the raw MSI pixel footprints and the orthoimage pixels necessitate a resampling of the raw MSI in the orthoimage. This resampling is needed regardless of the chosen GSD in decimal degrees or meters, if only because the pixels differ in shape and orientation between the raw MSI, and in their range of GSD values in both directions compared to the orthoimage.

Figure B-3. Default orthoimage pixel GSD in meters.



To explain the discrepancy, the meters of GSD for each direction (north or east) in the orthoimage are determined by different meters-per-angle increments on parallels compared with meridians in an ellipsoid-of-revolution. So the pixel is square with equal angular increments for longitude and latitude. However, the pixel becomes a rectangular with unequal dimensions in meters when comparing the east and north directions regardless of the projection. This implies that the spectral properties of the original imagery are perturbed by resampling without regard for how close the orthoimage output spatial resolution is to the nominal GSD of the raw MSI, or from the differences between the orientations of the footprint for the MSI coordinate frame and that of the produced orthoimage.

Each orthoimage pixel includes more than one terrain elevation value from the DEM given the dimensions used to best retain the spatial resolution of the raw MSI, unless the output pixel GSD for the orthoimage is reset at 1 m to match the spatial resolution of the DEM, which will result in one terrain elevation value for each orthoimage pixel. MSI feature extraction literature describes the advantages of having a single elevation value for each orthoimage pixel (Brown, 2013; Campbell & Wynne, 2011; Homer, et al., 2004; Longbotham, et al., 2012).

Figure B-4 shows the four corners of the entire MSI frame projected onto the terrain surface. This reflects the overall nearly parallelogram shape for the footprint of the entire MSI frame in the UTM coordinate system (Figure 2-13, p 20), and shows that the shape of each pixel matches that of the entire MSI frame.

Figure B-4. Raw MSI corners from NITF.

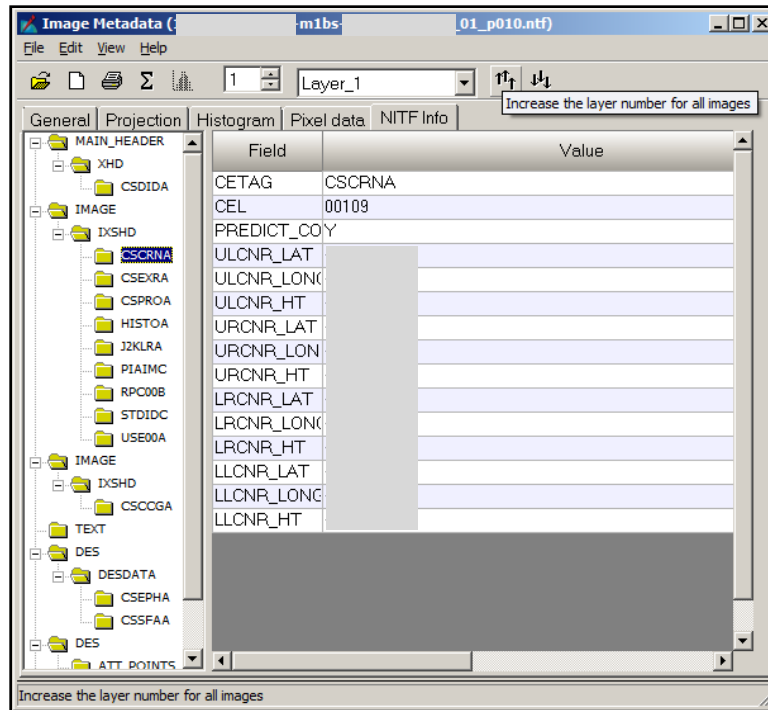
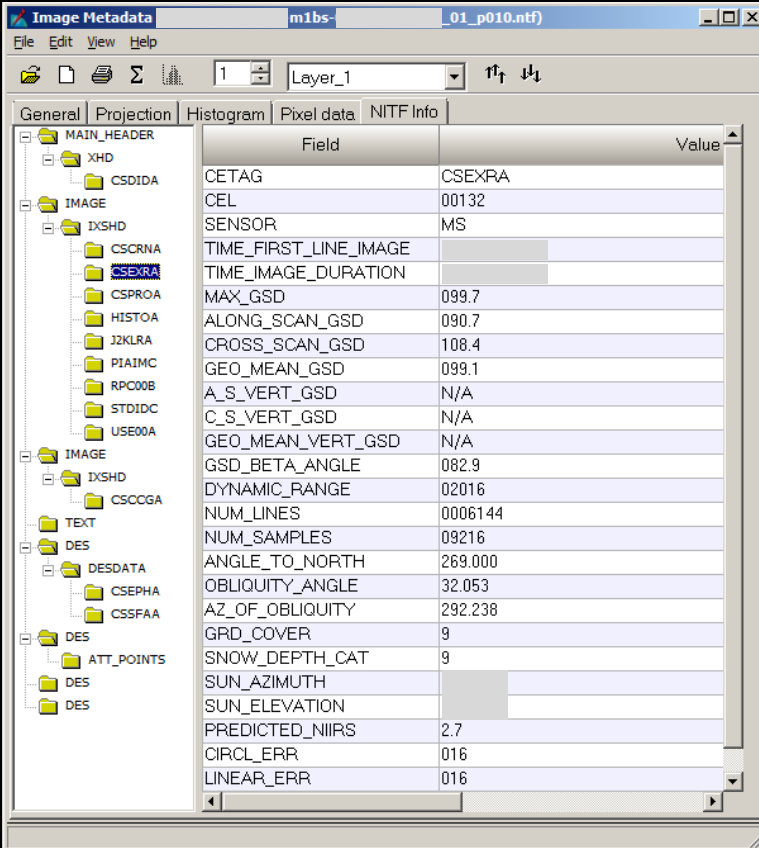


Figure B-5 shows the angles that reflect the satellite orbital mechanics, along its track velocity and across its track scan velocity, given its obliquity angle between the satellite nadir and vertical vector that is perpendicular to the terrain surface of the rotating earth. These angles cause the parallelogram shape of the frame and its pixels.

Figure B-5. Sensor orientation metadata from NITF.



Field	Value
CETAG	CSEXRA
CEL	00132
SENSOR	MS
TIME_FIRST_LINE_IMAGE	
TIME_IMAGE_DURATION	
MAX_GSD	099.7
ALONG_SCAN_GSD	090.7
CROSS_SCAN_GSD	108.4
GEO_MEAN_GSD	099.1
A_S_VERT_GSD	N/A
C_S_VERT_GSD	N/A
GEO_MEAN_VERT_GSD	N/A
GSD_BETA_ANGLE	082.9
DYNAMIC_RANGE	02016
NUM_LINES	0006144
NUM_SAMPLES	09216
ANGLE_TO_NORTH	269.000
OBLIQUITY_ANGLE	32.053
AZ_OF_OBLIQUITY	292.238
GRD_COVER	9
SNOW_DEPTH_CAT	9
SUN_AZIMUTH	
SUN_ELEVATION	
PREDICTED_NIIRS	2.7
CIRCL_ERR	016
LINEAR_ERR	016

Figure B-6 shows the produced orthoimage that is reset to equal the 1 m precision of the DEM raster, because the output resolution was reset to be 1 m in both of the X-east and Y-north directions. This was different from the default output resolutions for the orthoimage suggested by the software. More geometric distortions are removed from the raw MSI, however, when the better resolution of the DEM is fully used, compared to the orthorectification that only retains the nominal GSD of the raw MSI.

It is uncertain how the software estimates a terrain height when the X and Y position within the DEM is between actual posts within its raster. This might compromise the geometrical integrity of the output orthoimage when there are many elevation discontinuities between the posts with a terrain height, for example from buildings in an urban zone. One concerned with retaining the spectral integrity of the raw MSI should create a feature layer directly from the raw MSI, and then convert the thematic raster to an orthoimage. A separate process was developed to orthorectify the theme map from feature extraction in the raw MSI. (This is described elsewhere.)

Figure B-6. 1 m GSD Orthoimage Compared To 1 m GSD DEM Raster.

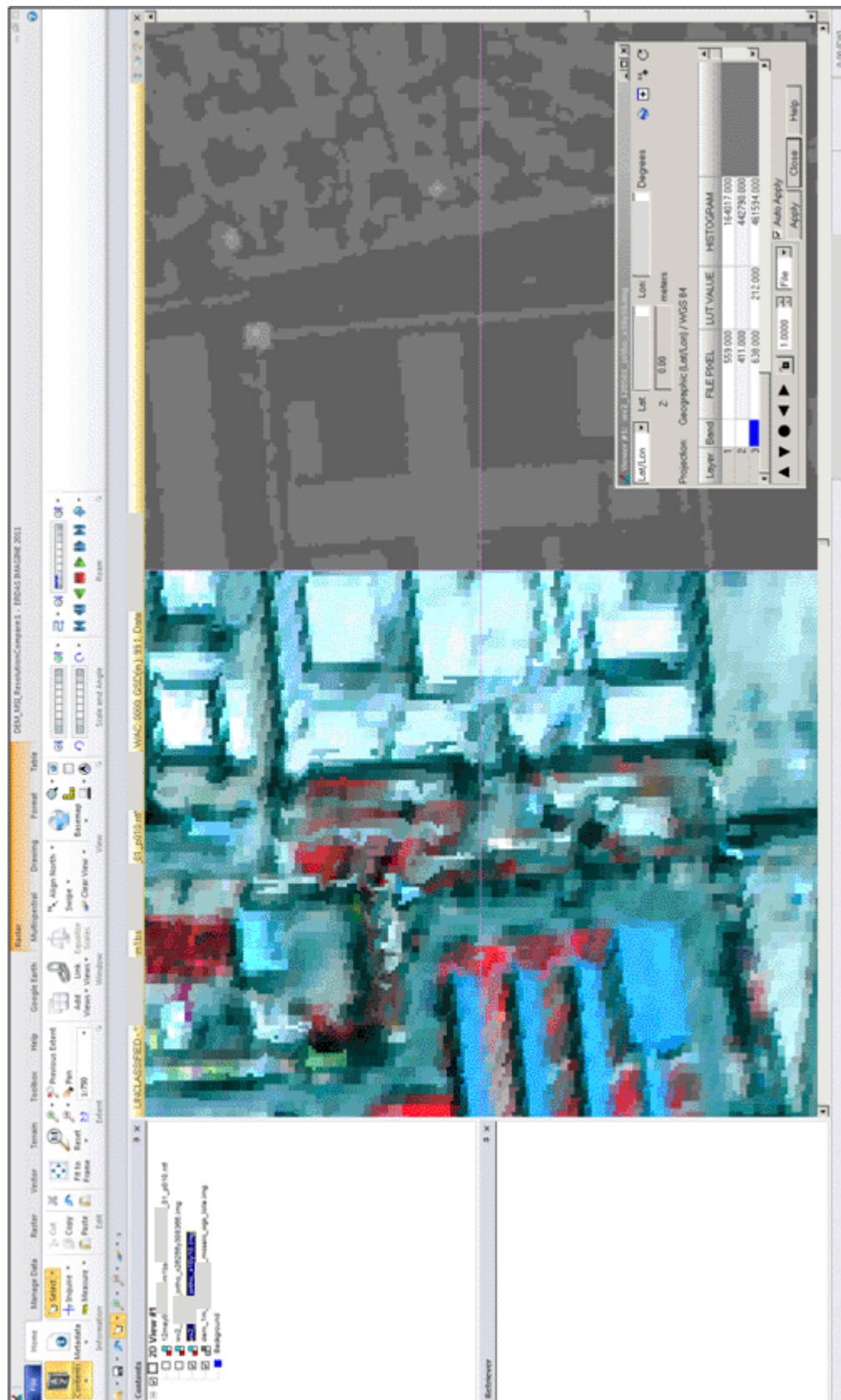


Figure B-7 and B-8 show the first three bands of the raw MSI pixel footprints from the first MSI frame (without the orthorectification process applied to it). Figure B-7 shows the DEM raster terrain height values posts overlaid onto the frame. Figure B-8 shows its produced orthoimage footprints in which the output spatial resolution suggested by the software is close to the nominal GSD of the pixel footprint (a parallelogram-like shape) from the raw MSI with the nominal average GSD (x:2.63 m by y:3.08 m). Figure B-9 shows the orthoimage produced with the same spatial resolution of the DEM raster (1 m x 1 m). This means that each pixel for the orthoimage with the default pixel dimensions contains 2-or-3 DEM spot values in the east-x-direction, and 3-or-4 DEM spot values in the north-y-direction. Each “pixel’s worth” of data from the orthoimage contains 6, 8, 9, or 12 DEM spots within the orthoimage that has the same spatial resolution suggested by the software.

The left side of Figure B-9 shows the result, within the viewer, of having an output spatial resolution for the orthoimage that matches the GSD of the DEM raster, alongside the orthoimage (shown on the right side of the viewer) that has the nominal spatial resolution of the raw MSI. Note that the edges of buildings are smoother when the orthoimage uses the better spatial resolution of the DEM raster. There also is one terrain height DEM value for each pixel of the orthoimage when they become registered together through the orthorectification process, and when the output spatial resolution of the orthoimage matches the GSD for the DEM.

This implies more geometrical rectification within the orthoimage that retains the GSD of the DEM with better resolution than the raw MSI. A single elevation value for each orthoimage pixel results from projecting each DEM post into the raw MSI space, so there is one DEM terrain height value for each orthoimage pixel. This makes it possible to add terrain heights, or derivatives such as slope and aspect, as extra channels or layers into the MSI to enhance feature extraction, because the features are automatically registered to the orthoimage through the process of producing it. If the full resolution of the DEM is used in the orthorectification process, each orthoimage pixel is the result of one known elevation value.

Figure B-7. Raw MSI and DEM raster terrain height posts.

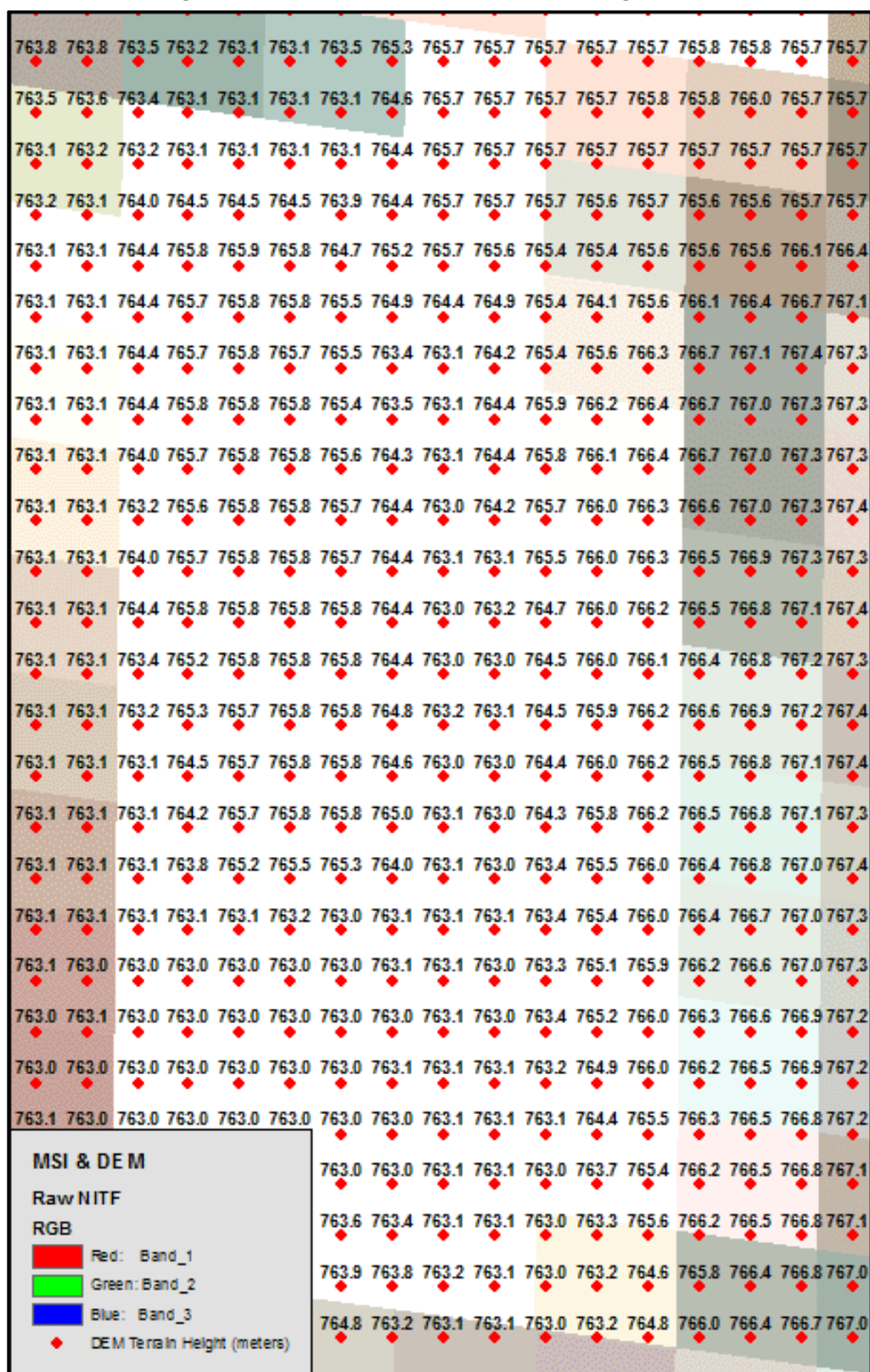


Figure B-8. Orthoimage with nominal GSD of raw MSI and DEM posts.

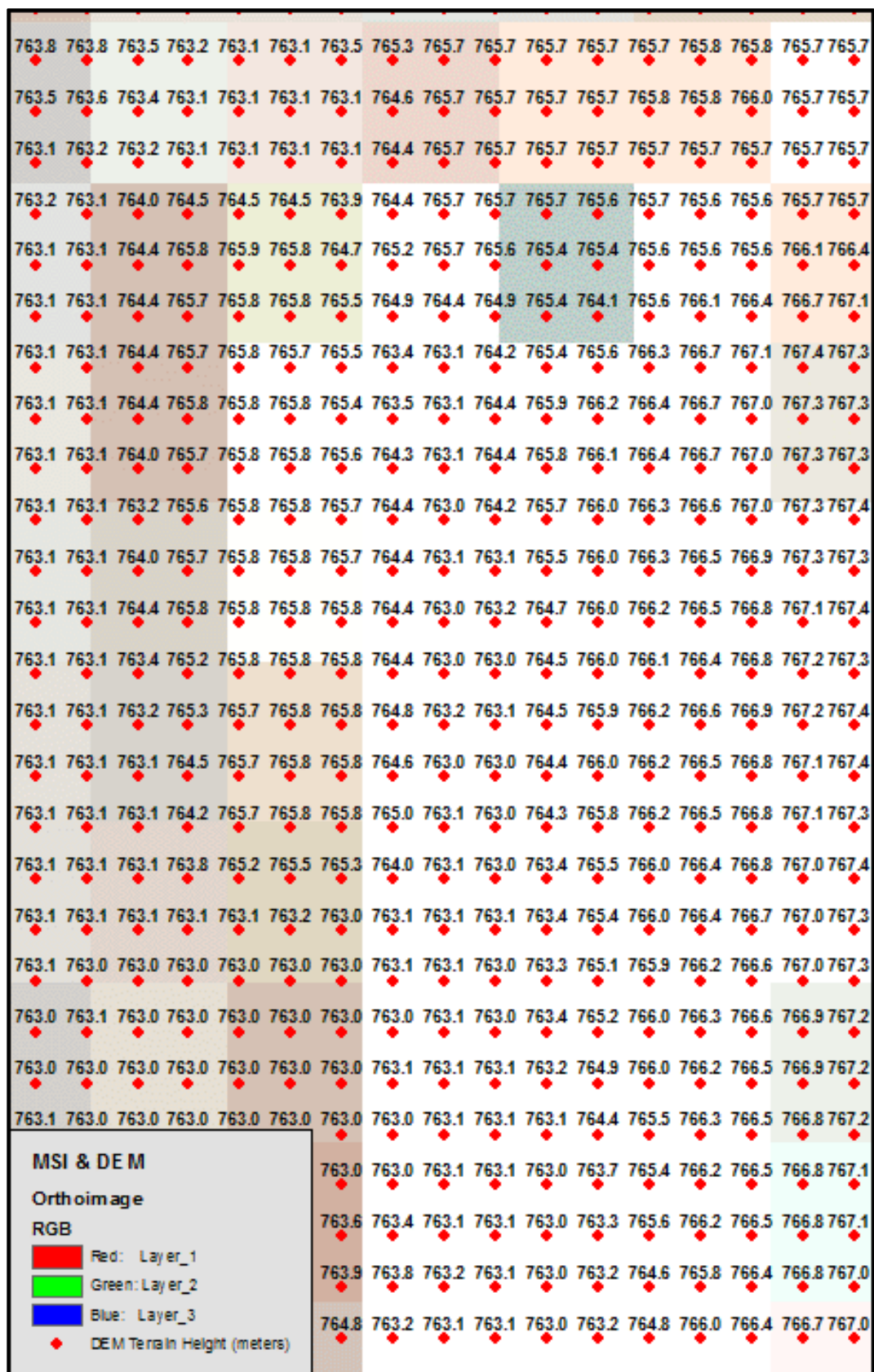
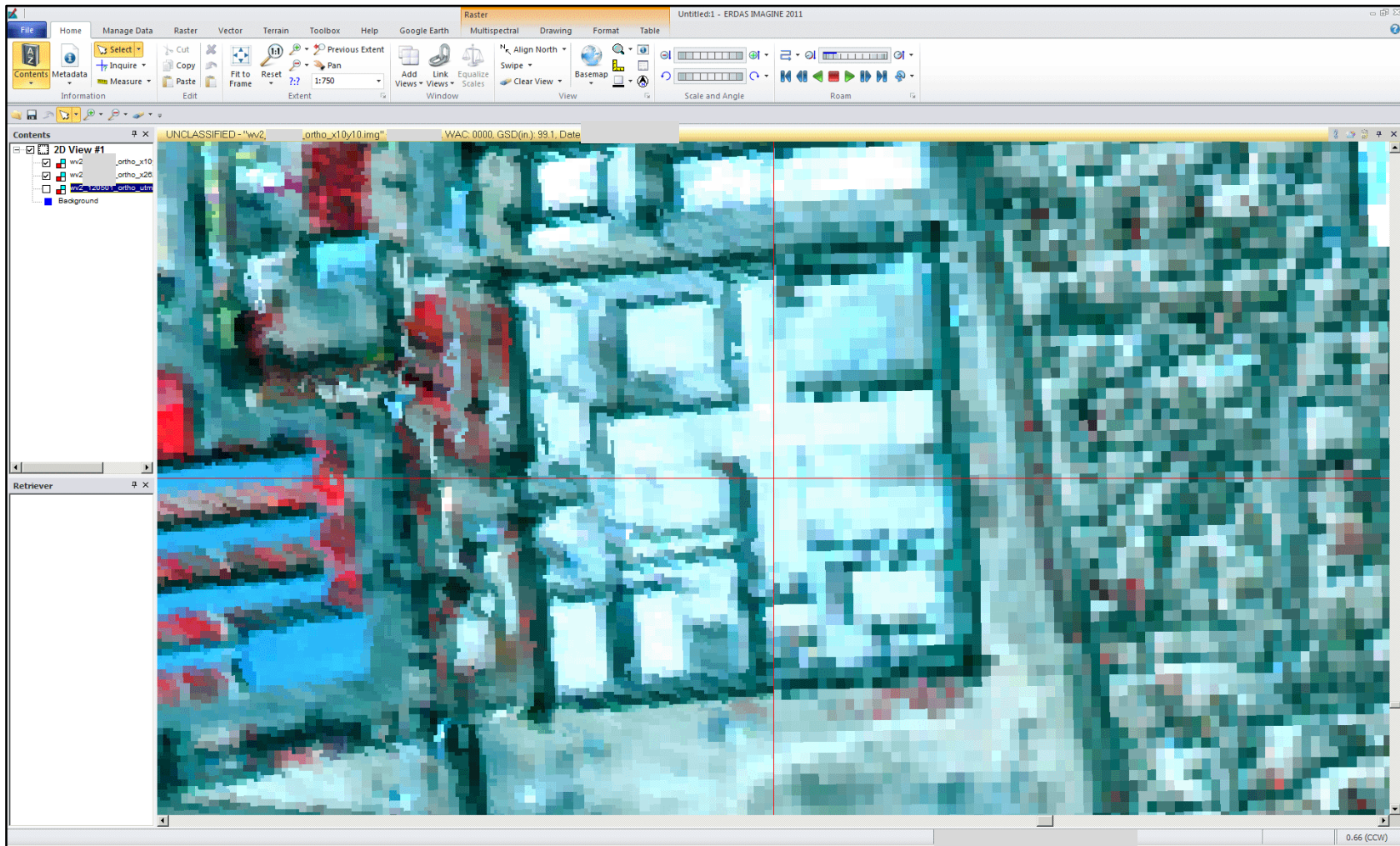


Figure B-9. 1 m GSD orthoimage compared x:3.09 by y:2.63 GSD orthoimage.



Chapter 2, “Procedures,” sought to clarify the output spatial resolution by using the values suggested by software. However, this appendix section has further explained some important spatial and spectral concerns that should be considered when choosing the output spatial resolution of the produced orthimages, described as optional steps in Chapter 2 (p 37).

Specifically, this appendix has explained why the output spatial resolution of the orthoimage could be something besides the nominal GSD of the raw MSI suggested by the software. The geometric accuracy of each orthoimage and of the mosaic also might be compromised if the nominal GSD of the raw MSI suggested by the software is used instead of some other specified value.

Appendix C: RPC Projective Equations

Equations C-1 and C-2 show how current commercial image processing software projects each DEM grid-cell with a terrain elevation value z from the ground into the MSI raster by using the RPC (Tao & Hu, 2001). This replaces the actual sensor model to produce new orthoimages with distortions removed from its raw image. This pair of equations forms two quotients, each with a ratio of two polynomials called rational functions for multiple variables, such as DEM raster grid cells (x, y, z) transformed to pixels in image space (x', y') .

$$[x, y, z]_{DEM} \rightarrow [x', y']_{MSI}:$$

$$\begin{aligned} x' &= \frac{P(x,y,z)}{Q(x,y,z)} = \frac{\sum_k \sum_j \sum_i (a_{ijk})_p (x^i)(y^j)(z^k)}{\sum_k \sum_j \sum_i (a_{ijk})_q (x^i)(y^j)(z^k)} \\ y' &= \frac{R(x,y,z)}{S(x,y,z)} = \frac{\sum_k \sum_j \sum_i (a_{ijk})_r (x^i)(y^j)(z^k)}{\sum_k \sum_j \sum_i (a_{ijk})_s (x^i)(y^j)(z^k)} \end{aligned} \quad (C-1)$$

where:

a_{ijk} = the RPC delivered along with the MSI [for example the $(a_{221})_p$ coefficient is for the $(a_{221})_p (x^2)(y^2)(z^1)$ term in the numerator for the rational polynomial].

P and R = functions in the numerators for the equations

Q and S = functions in the denominators for the equations

P , Q , R , and S each have a different set of coefficients, say $\{P: (a_{ijk})_p\}$ for example, where there is a different coefficient for each product of x raised to the i^{th} power, y raised to the j^{th} power, and z raised to the k^{th} power.

Equations C-2 show how the $[x, y, z]$ coordinates of the DEM space and the $[x', y']$ coordinates of the MSI space are actually offsets from each of the defined perspective center of both spaces to normalize the RPC model. These centers of each space are contained in the NITF along with the RPC. Consequently, these coordinates are components of the projective vector from DEM space into MSI space.

$$\begin{aligned} x &= x - x_0 \\ y &= y - y_0 \\ z &= z - z_0 \\ x' &= x' - x'_0 \\ y' &= y' - y'_0 \end{aligned} \quad (C-2)$$

Appendix D: Orthoimage Mosaic

An orthoimage mosaic is produced similarly to the way that a LiDAR DEM mosaic was created in Section 2.3 of the Chapter 2, “Procedures,” except that each separately produced orthoimage within the mosaic is listed instead of each LiDAR DEM shown in Section 2.3.

It is sufficient to understand Section 2.3 of the tutorial to determine the necessary processing steps for combining the MSI orthoimages into a single mosaic, if one simply generalizes the process to create a mosaic from orthoimages instead of DEM rasters. If each orthorectification has a different output spatial resolution, a choice still needs to be made about the overall GSD of the orthoimage mosaic. This will result in another sampling of each orthoimage that does not have the same GSD as the output mosaic.

Appendix E: Earth Gravity Model Terrain Heights

Figures E-1 and E-2 show an example of the WGS84 ellipsoid and EGM96 geoid height at the same UTM coordinates of [redacted] m east and [redacted] m north (Lemoine, et al., 2004). The difference between the elevations for each of the two vertical datums (shown in the “FILE PIXEL” field) indicates that the geoid is about 24 m below the ellipsoid ([redacted] m minus [redacted] m = 24.290 m). Repeated measurements across the entire DEM show a slight variance for this elevation difference of less than 1 m because the geoid values vary slightly throughout the entire DEM. This approximately 24 m of vertical error within the DEM will propagate throughout the RPC DEM-to-MSI projection unless the terrain heights are converted from EGM96 to WGS84 before making the orthoimage.

Figure E-1. WGS84 ellipsoid height.

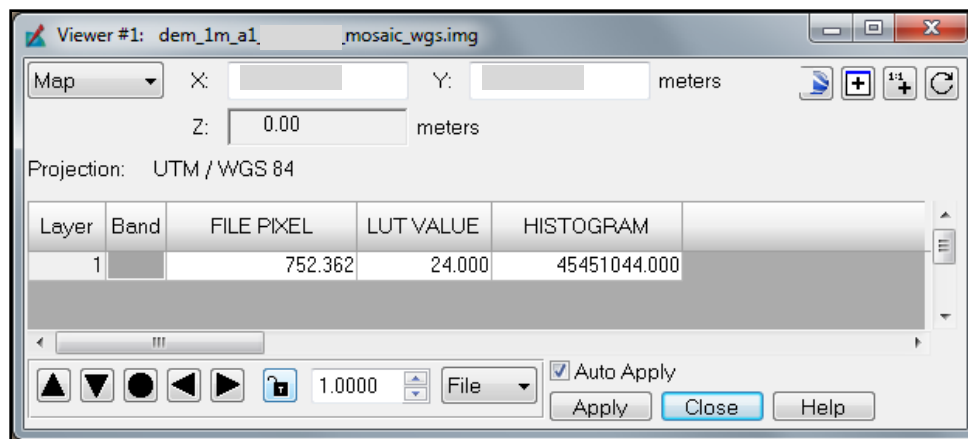
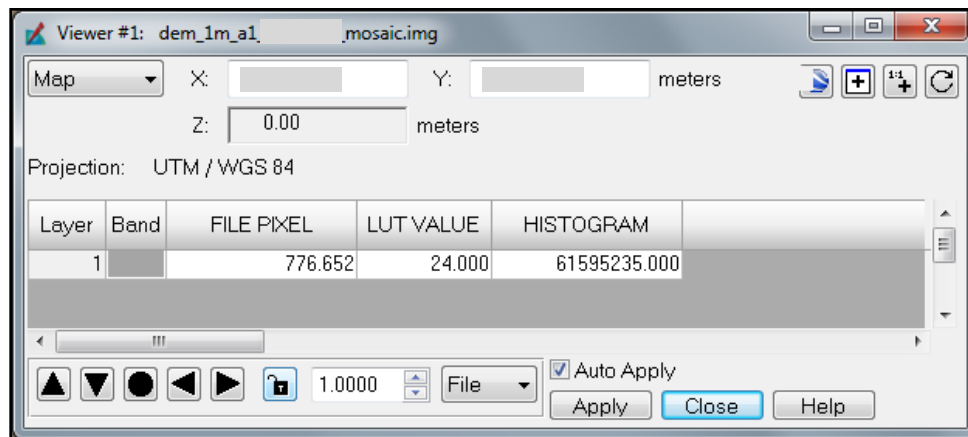


Figure E-2. EGM96 geoid height.



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14. ABSTRACT Orthoimages are used to produce image-map products for navigation and planning, and serve as source data for advanced research, development, testing, and evaluation of feature extraction methods. This tutorial describes procedures for making orthoimages from Light Detection and Ranging (LiDAR) Digital Elevation Models (DEM) and from commercial satellite Multi-Spectral Imagery (MSI) in the National Imagery Transmission Format (NITF) with Rational Polynomial Coefficients (RPC). Orthoimages rectify digital imagery to remove geometric distortions caused by the varying elevations of the exposed terrain features, and by exterior and interior orientations of the sensor. When orthoimages are combined, the resulting mosaic covers a wider area and contains less visible seams, which makes the map easier to understand. RPC replace the actual sensor model while processing the original MSI. This generic replacement sensor model is provided with the distributed imagery to simplify the process of removing the geometric distortions so image processing software can create orthoimages without using the actual sensor model, which is often not provided. The DEM and MSI also become better registered together after producing the orthoimage by using the RPC. This assists feature extraction and segmentation when the DEM is added as extra data bands to the MSI.					
15. SUBJECT TERMS LiDAR, satellite imaging, aerial imagery, orthoimages, remote sensing					
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